

The solidus of harzburgite to 3 GPa pressure: the compositions of primary abyssal tholeiite

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Summary

Abyssal tholeiite is generated by partial melting of the upper mantle. The mantle sections of ophiolite complexes show that partial melting leaves mantle residua that are lherzolithic or harzburgitic, harzburgite being the more depleted residuum. It is shown that some of the interstitial melt of partially molten harzburgite approximates a tholeiitic composition. Therefore, the solidus of harzburgite constitutes the maximum possible temperature for the generation of primary tholeiite. The MgO contents of primary tholeiites in equilibrium with harzburgite are determined to be about 21 and 23 wt.% MgO at 2.0 and 3.0 GPa, respectively. The possible MgO contents of primary abyssal tholeiite is suggested to range between 10 and 23 wt.% MgO, with the MgO content increasing with increasing pressure.

Introduction

The estimation of the compositions of primary magmas represents one of the more fundamental problems in igneous petrology. By partial melting of the mantle three basaltic suites are generated, the nephelinitic, alkalic and tholeiitic suites. These suites form linear major element trends that may either be caused by fractionation or by varying degrees of partial melting. The tholeiitic suites form olivine controlled trends which are caused both by olivine fractionation and accumulation. The magma from which olivine accumulates and fractionates is called the parental magma (*Rhodes*, 1995). The initial composition of the magma that was extracted from the partially molten lherzolite is called the primary magma. If the primary magma ascends without fractionation, then the parental and primary magmas have identical compositions. The compositions of the primary tholeiitic magmas are not

immediately obvious because estimation of the composition of a parental magma is only possible from a tholeiitic trend. A tholeiitic trend may originate from magmas that underwent fractionation during their ascent through the lithosphere, so that the parental magma has a smaller MgO content than the primary magma. The presence of tabular dunite bodies in the mantle section of ophiolite complexes show that the ascending magmas must have crystallized olivine, so that their MgO contents decreased during ascent (*Quick, 1980*).

If the residue of a primary magma is known then its composition might be used to estimate the composition of the primary magma. The residua for the primary magmas of the nephelinitic and alkalic suites are not known. However, harzburgite is known as a typical residuum for abyssal tholeiites from the evidence of ophiolite complexes (*Coleman, 1977*). Residua with harzburgitic compositions may be more prevalent than is evident from the compositions of peridotite. If the solid part of a residuum consists of olivine and orthopyroxene, then the composition of the consolidated residuum depends on the extent of melt extraction. By an incomplete melt extraction the composition of the consolidated residuum becomes lherzolitic, and not harzburgitic. The present work presents an estimate of the compositions of primary tholeiites generated in equilibrium with residual harzburgite.

The MgO content of most abyssal tholeiitic lavas range from 4 to 9 wt.% MgO. Dredged lavas with higher MgO contents, within the range of 10 to 20 wt.% MgO do occur but are relatively rare (*Maaløe, 1979*). The MgO contents of Hawaiian tholeiitic lava range from 6 to 32 wt.% MgO (*MacDonald and Katsura, 1964; Maaløe et al., 1989; Frey and Rhodes, 1993; Rhodes, 1996*). The trends above 10 wt.% MgO are linear and olivine controlled, but it is not immediately obvious which parts of the trends are caused by olivine phenocryst fractionation and which by accumulation. By using the olivine-melt Fe–Mg KD relationship it is possible to estimate the maximal MgO content of a tholeiitic composition in equilibrium with olivine to be 17.4 wt.% MgO for Hawaiian tholeiites (*Roeder and Emslie, 1970; Ulmer, 1989; Garcia et al., 1995*). When using the Fe–Mg KD relationship, it should be kept in mind that some olivines may be xenocrysts, in which case the determined MgO contents may be too high. Furthermore, the forsterite content of olivine in equilibrium with a given tholeiitic composition decreases with increasing pressure (*Ulmer, 1989*). The MgO content of a parental magma may therefore be higher than is apparent from the maximal forsterite content of olivine phenocrysts. Olivine phenocrysts with high forsterite contents are rarely reported from the lavas of ophiolite complexes. Exceptions include the Curacao ophiolite complex where tholeiitic lavas contain resorbed olivine megacrysts with Fo_{91.4}, which indicate an MgO content of the lavas of about 18 wt.% MgO (Table 2) (*Beets et al., 1982*), and the Troodos ophiolite complex where tholeiitic lava contain olivine phenocrysts with Fo₉₁ (*Cameron, 1985*). These high-MgO tholeiitic compositions might still have undergone olivine fractionation during their ascent. The major problem is therefore to estimate the maximum possible MgO contents of primary tholeiites.

Apart from komatiites, primary tholeiites are the basalts generated at the largest degrees of melting. The extraction of tholeiitic melts leaves a residuum that is either lherzolitic or harzburgitic, depending on the degree of melting and the extent of melt extraction. By an increasing degree of melt extraction the depletion of the residuum increases. Harzburgite is present in most of the mantle sections of ophiolite

complexes, Alpine peridotite massifs, and dredged peridotites, and is the most depleted residuum left after extraction of primary tholeiitic melt. The solidus temperature of harzburgite therefore constitutes the maximal possible temperature at which primary tholeiites are generated. It should be noted, however, that primary tholeiite also can leave lherzolitic residua, so that not necessarily all tholeiitic residua are harzburgitic (*Elthon and Scarfe, 1984; Elthon, 1990, 1984; Walter, 1998*).

The solidus of a harzburgitic composition was therefore estimated at pressures up to 3.0 GPa. The starting material chosen is a harzburgite, specimen 62127 (Table 2), from the Horoman massif kindly supplied by *F.A. Frey* (*Frey et al., 1991*). This harzburgite contains 45.1 wt.% MgO and has a molar Mg/(Mg + Fe) ratio of 0.91. The mode of this harzburgite is estimated as 77.9 vol.% olivine, 19.6 vol.% orthopyroxene, 1.9 vol.% clinopyroxene, and 0.54 vol.% spinel (*Frey et al., 1991*). The range in MgO-contents of the lherzolitic-harzburgitic trends from ophiolite complexes, ocean dredges, and peridotite nodules are generally within 37 to 48 wt.% MgO (*Maaløe and Aoki, 1977; Paris, 1981; Frey et al., 1985; Lippard et al., 1986; Frey et al., 1991; Snow and Dick, 1995; Niu, 1997; Werner and Pilot, 1997; Takazawa et al., 2000*). The most detailed estimated trends, the Horoman and La Ronda trends, display a kink at 45 to 46 wt.% MgO (*Frey et al., 1985; Takazawa et al., 2000*). A similar kink is observed for a global suite of dredged peridotites (*Baker and Beckett, 1999*). The part of the lherzolite trends with less than 45 wt.% MgO are linear and extrapolate towards an estimated primary composition of abyssal tholeiite, which suggests that they are controlled by tholeiitic melt extraction (*Maaløe and Steel, 1980; Frey et al., 1985*). The harzburgite composition 62127 therefore represents an MgO-rich end composition of the linear lherzolitic-harzburgitic part of the trend.

Experimental and analytical methods

The solidus of the harzburgite was determined with piston-cylinder experiments between 1.0 and 3.0 GPa. The harzburgite was ground to 5–10 μm in grain size, dried at 900 °C, and then kept at 200 °C. The furnace assembly contained anhydrous parts only, like alumina, silica, and pyrex glass, as well as graphite and stainless steel (Fig. 1). The charge was placed in a 3 mm inner-diameter graphite cylinder with 1 mm wall thickness, and enclosed in a welded platinum cylinder with 0.2 mm wall thickness. The temperature was controlled using ReW5/ReW26 thermocouples and a West-Viscount temperature controller. The furnace assemblage was flushed with argon before and during initial pressurization, in order to avoid oxidation of the thermocouple. The run duration varied between 24 and 120 hours (Table 1). The run procedure used was described by *Maaløe and Jakobsson (1980)*. Pressure and temperature were calibrated using the melting curve of diopside (*Williamson and Kennedy, 1969*). Pressure is accurate within ± 0.03 GPa, and temperature within ± 25 °C.

The ($^{226}\text{Ra}/^{230}\text{Th}$) activity ratios of natural tholeiitic basalts show that the percentages of interstitial melt in partially molten lherzolite is about 1% or less (*Salter and Longhi, 1999*). The compositions of the synthetic interstitial glasses should therefore be estimated when about 1% glass is present in the harzburgitic charges. The diamond/vitreous carbon method for isolating an interstitial melt could therefore not be applied (*Hirose and Kushiro, 1993; Schwab and Johnston,*

Furnace assemblage

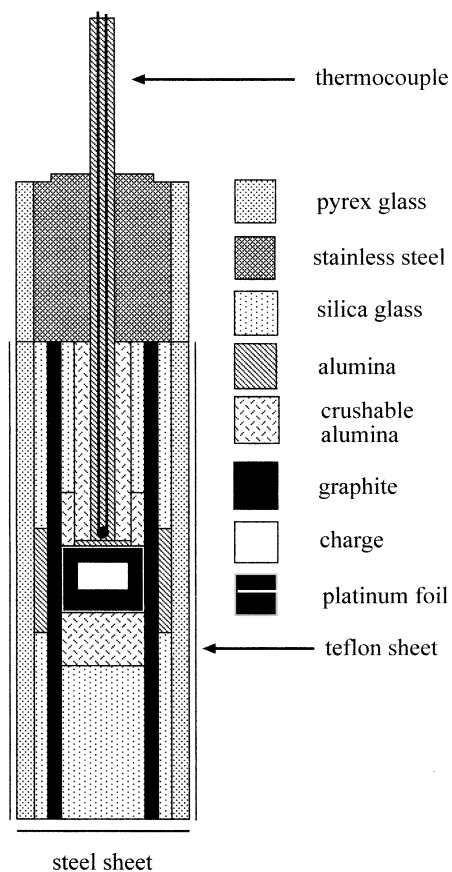


Fig. 1. The 1/2 inch furnace assembly used consists of water-free parts only. The charge is enclosed in a spec-pure graphite cylinder, which is encapsulated in a welded platinum container. The graphite furnace is surrounded by solid alumina near the charge, to diminish irregular deformation of the graphite furnace, which changes the temperature gradient. With this furnace assemblage, the 36 mm long cylindrical graphite furnace retains its cylindrical shape. At high temperatures silica and pyrex glass become viscous and impose hydrostatic conditions. A teflon sheet around the assemblage is used to decrease friction during pressurization

Table 1. Run conditions (*r*: reversed runs, *trace*: less than 1%)

Pressure GPa	Temperature °C	Duration hours	Glass
0	1400	24	none
0	1430	20	trace
1.0	1450	48	none
1.0	1500	25	2%
1.0	1550	120	trace
1.0	1650	24	12%
2.0	1500	24	none
2.0	1550	24	trace
2.0	1600	48	4%
2.0	1650	24	trace
3.0	1620	15	none
3.0	1650	20	trace
3.0	1700	21	trace
1.0	1600–1500r	24	1%
1.0	1600–1550r	48	1%

2001). The compositions of the interstitial melts in these experiments are therefore modified by quench growth of olivine and orthopyroxene. Two runs were reversed by 50 °C and 100 °C, in order to test the attainment of equilibrium. The reversed runs were held at a high temperature for 24 hours, and thereafter temperature was decreased by 5 °C/h to run temperature. Subsequently, temperature was held constant for 24 and 48 hours. The temperature reversal was kept slow at 5 °C/h in order to avoid quench growth. The charges were investigated in reflected light and analyzed with a Jeol scanning electron microscope in the energy-dispersive mode.

Experimental results

The estimated harzburgite solidus is shown in Fig. 2 and compared with estimated lherzolite solidi (*Takahashi, 1986; Kushiro, 1996; Walter, 1998*). The lherzolitic

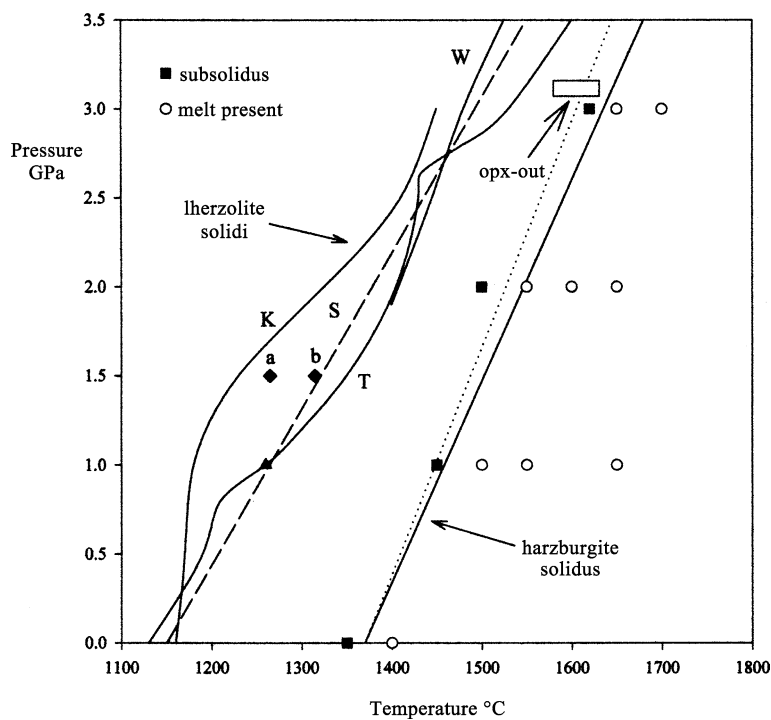


Fig. 2. Estimated solidus curve for harzburgite with 45 wt.% MgO compared with solidi for lherzolite (*Takahashi, 1986; Kushiro, 1996; Walter, 1998*). The dashed line S is suggested to be a representative solidus for lherzolite. The triangle shows the solidus estimated by *Schwab and Johnston (2001)*, and the two diamonds represent the solidi estimated by *Robinson et al. (1998)*, for lherzolite with 38.4 (a) and 39.7 wt.% MgO (b). The solid line shows the temperature-corrected solidus for harzburgite, and the dotted line the solidus without a temperature correction. The opx-out temperature is the melting temperature of orthopyroxene. The lherzolite solidi and the opx-out temperature bracket are estimated without pressure corrections for the temperature. The opx-out temperature bracket, shown as a rectangle, was estimated for a lherzolitic composition with 37.3 wt.% MgO (*Walter, 1998*). The opx-out temperature for an average lherzolite with 42 wt.% MgO will be higher. The MgO contents of the lherzolitic compositions are, K: 37.2 wt.% MgO, W: 37.3 wt.% MgO, and T: 39.2 wt.% MgO

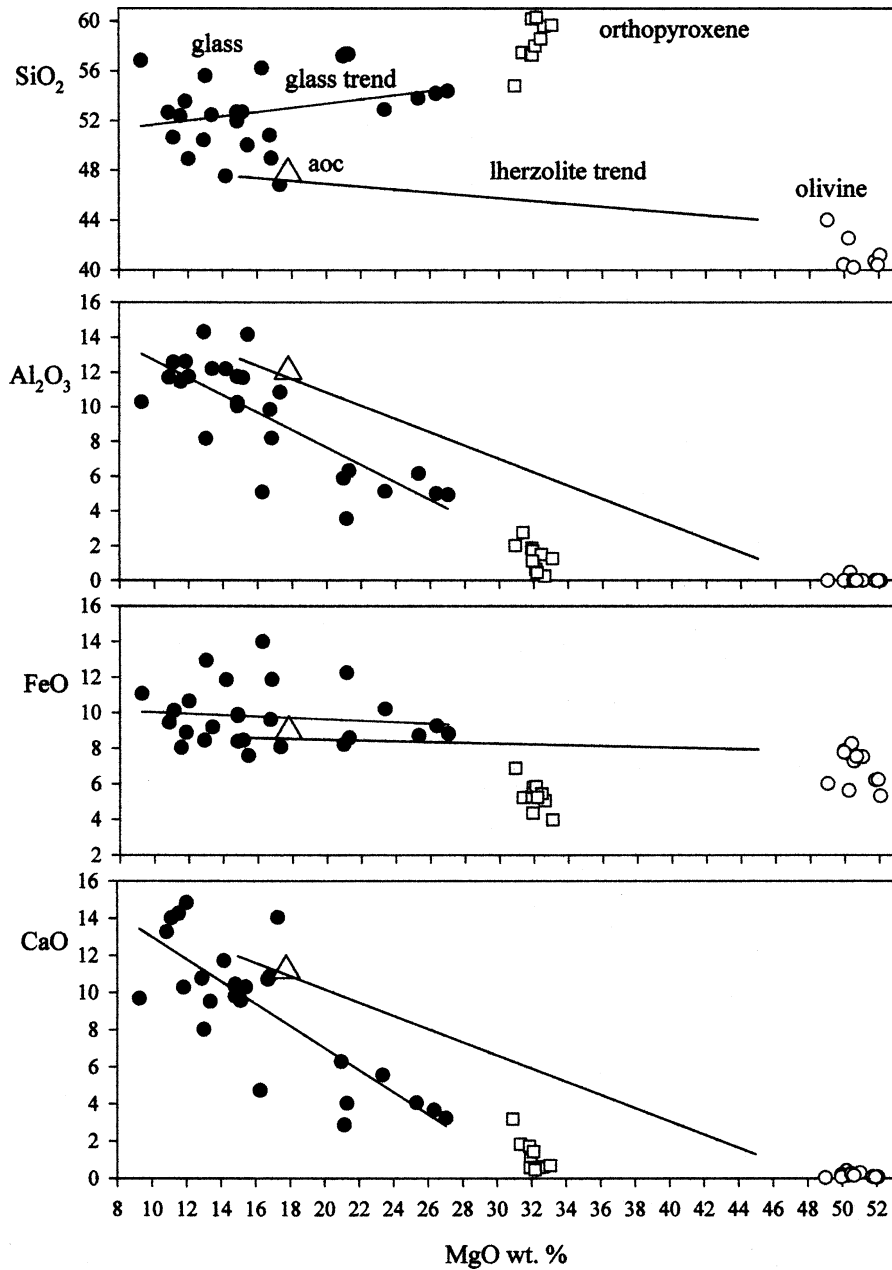


Fig. 3. Glass compositions obtained at pressures between 1 and 3 GPa. Most glasses have lost MgO by olivine quench growth. The scatter in the analyses is partly due to quenching and partly attributed to differences in the minerals surrounding the melt patches. Most of the glasses have high SiO₂ contents because their melts were generated from olivine and orthopyroxene only. These glasses define the glass trend. The compositions of olivine and orthopyroxene are also shown. The Iherzolite trend is the trend for the Horoman Iherzolite estimated by regression analysis from the data of *Takanazawa et al. (2000)*. An estimated average composition of the oceanic crust is shown by the triangle (aoc, *Elthon, 1979*)

compositions vary in their MgO contents from 37.2 to 39.2 wt.% MgO. The differences in the lherzolite solidi are partly related to different compositions and methods of estimation. The dashed line "S" in Fig. 1 is considered as a representative lherzolite solidus. The solidus of harzburgite is situated 150 to 200 °C above the solidus of lherzolite. The difference in temperature decreases with increasing pressure (Fig. 2). Considering that lherzolite is a four-solid system and harzburgite a two-solid system, it is expected that the solidus of harzburgite is situated at higher temperatures than the solidus for lherzolite.

The percentages of interstitial melt are about or less than 1% within 50 °C of the solidus. This small amount of melt is considered real, because reversed runs also yielded a similar amount of melt. Quench growth is evident from backscatter images, i.e. olivine and orthopyroxene both developed 3 to 5 µm wide rims towards the 10 to 30 µm large glass inclusions. The glass in a large melt pocket in a 1.0 GPa run is unmodified by quenching and contains 21 wt.% MgO, while the glass in small melt patches from the same run only contain 8 wt.% MgO due to quench growth of olivine. The crystals surrounding the melt are faceted and euhedral, which suggest attainment of equilibrium. The compositions of the interstitial glasses, orthopyroxene, and olivine are shown in Fig. 3. The SiO₂ contents of the glasses range from 48 to 56 wt.% SiO₂, and the MgO contents range from 8 to 27 wt.% MgO. The SiO₂ contents of the SiO₂ rich glasses show that they consist of about 85 wt.% normative orthopyroxene and 15 wt.% normative olivine. The forsterite-enstatite phase relations are peritectic below 0.8 GPa and become eutectic above this pressure (Boyd and England, 1963). At 0.8 GPa the peritectic point has the same composition as enstatite. A large orthopyroxene content of the initial melt is therefore expected at 1 to 3 GPa. The SiO₂ concentrations of most of the glasses are higher than in a primary abyssal tholeiite with 18 wt.% MgO, which is about 48 wt.% SiO₂ (Fig. 3).

Discussion

The interstitial glasses synthesized in these experiments vary in composition due to quench growth of olivine and orthopyroxene. In addition, the melt was generated in equilibrium with either olivine and orthopyroxene, or olivine, orthopyroxene and clinopyroxene. The small amount of clinopyroxene in the starting material, i.e. 1.9 vol.%, implies that only a minor fraction of the interstitial melt patches were in contact with clinopyroxene. Since there is a solvus between clinopyroxene and orthopyroxene, it is possible that clinopyroxene becomes increasingly subcalcic with increasing temperature to eventually dissolve in orthopyroxene (O'Hara and Yoder, 1967; Nehru and Wyllie, 1974). However, in this case the melt is formed from olivine and a Ca-rich clinoenstatite. The presence of two different solid phase assemblages, S(ol,opx) and S(ol,opx,cpx), in the experimental charges probably mimic the phase assemblages in natural harzburgite where most of the melt was extracted, leaving isolated melt patches.

The compositions of the interstitial glasses do not deviate all that much from tholeiitic compositions, but most of the glasses have silica contents of 50 to 56 wt.%, which are too high for typical tholeiitic compositions. The melt of these glasses must have formed in equilibrium with olivine and orthopyroxene only.

Most of the glasses have MgO contents below 14 wt.% MgO which are considered artificially low due to quench growth of olivine and orthopyroxene. Some of the glass compositions have relatively large CaO contents, and are situated near or around an estimated average composition of the oceanic crust (aoc, Fig. 3; *Elthon*, 1979). These compositions are also situated near the extrapolated trend for the Horoman lherzolites (Fig. 3).

In order to interpret these results, the basic phase relations of melt extraction should be considered. A ternary system with two solid phases, α and β , which both have solid solutions, is shown in Fig. 4. The initial composition is "L" (Lherzolite). When it undergoes partial melting, the first melt has composition "l". When the melt reaches composition "h", the melt is extracted so that the total composition changes from "L" to "H" (Harzburgite). Conversely, when a solid consisting of solids α_h and β_h with total composition "H" is melted, the first melt has composition "h" and the temperature of the solidus is higher than that of "L". The first melt that forms by melting of "H" therefore has the same composition as the composition of the last melt that was extracted (*Yoder*, 1976). With this in mind the melt generated by partial melting of harzburgite should have a tholeiitic composition, if the last melt extracted was tholeiitic. Further, the mineral proportion in the residual harzburgite should equal those in the partially molten lherzolite. As is evident from Fig. 3 the glasses with large CaO contents have compositions near the estimated average

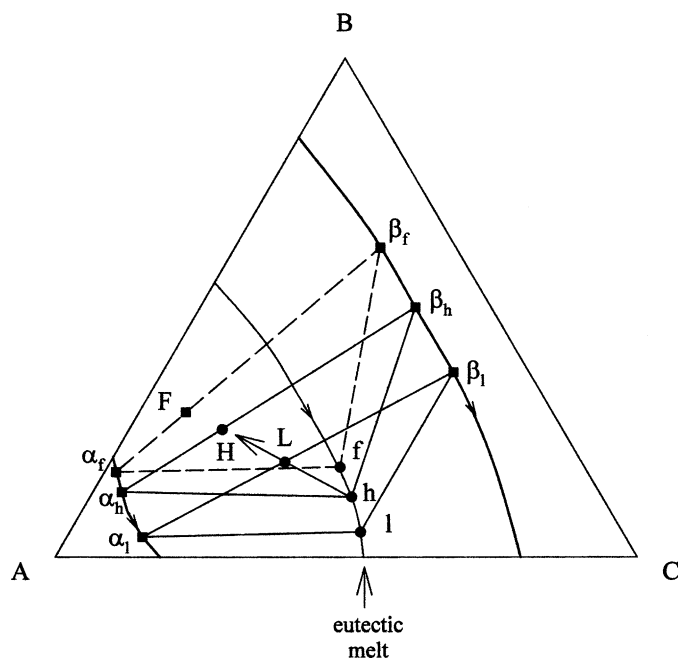


Fig. 4. A ternary system with two solid phases α and β with solid solution. The first melt is generated with composition "l". When the melt attains composition "h" it is extracted, changing the bulk composition of the system from "L" to "H". By batch melting of composition "H" the first generated melt has composition "h". With critical melting, the composition of the residuum becomes more refractory and may attain a composition like "F", which has a higher solidus temperature than "H"

composition of the oceanic crust and the extrapolated lherzolite trend line. It is therefore considered justified to assume that the harzburgite was generated by an extraction of a tholeiitic melt. The lherzolitic layers situated just above the harzburgite layers of the Horoman massif are enriched in a tholeiitic component (*Obata and Nishimoto, 1992; Takazawa et al., 2000*). The compositions of the lherzolite of the Horoman massif form linear trends which show that the extracted melts had nearly constant compositions. A similar feature is observed for the La Ronda massif (*Frey et al., 1985*). The depletion of the harzburgite is therefore caused by an almost complete extraction of an interstitial tholeiitic melt. The horizontal layering of the Horoman massif suggests that the partially molten lherzolite underwent compaction, so that the melt extraction probably was caused by compaction.

Another basic phase relationship is evident from Fig. 4. If composition “H” is generated by batch melting in equilibrium with melt “h”, then the residual composition “H” will start to form melt with composition “h”. If, on the other hand, the melting mode is critical and the residual composition “F” is generated, then the solidus temperature of “F” will be higher than that of “H”, and the composition of the melt will be “f” instead of “h”. Hence, if harzburgite is generated by critical melting its solidus temperature will be higher than the temperature of the opx-out batch melting temperature of lherzolite.

Unfortunately, the opx-out temperature for lherzolite was estimated at widely different temperatures. The opx-out curve was bracketed between 1580 °C and 1630 °C at 3.0 GPa by *Walter (1998)*, the uncorrected solidus temperature of harzburgite being estimated as 1600 °C at 3.0 GPa (Fig. 2). The lherzolitic composition used contains 37.3 wt.% MgO, so that the opx-out temperature should be higher for lherzolite with higher MgO contents. However, *Takahashi (1986)* estimated the opx-out temperature at 1580 °C at 3.0 GPa for a lherzolitic composition with 39.2% MgO, and did not observe orthopyroxene within the melting interval at pressures above about 3.5 GPa, while *Walter (1998)* identified orthopyroxene at pressures up to 7.0 GPa. The opx-out for a lherzolite with 41.6% MgO curve was estimated at a much higher temperature at 3.0 GPa, about 1850 °C by *Ito and Kennedy (1967)*. Their 3.0 GPa experiments were of less than 30 min duration, so that equilibrium may not have been attained. The melting behavior of a lherzolitic composition with 37.2 wt.% MgO was estimated at 2.0 GPa and 3.5 GPa by *Mysen and Kushiro (1977)*, the interpolated opx-out temperature at 3.0 GPa being 1705 °C. The reported opx-out temperatures at 3.0 GPa thus range from 1580 to 1705 °C (1850 °C) for lherzolites with 37.2 to 41.6 wt.% MgO. A higher solidus temperature for harzburgite than the equilibrium opx-out temperature for lherzolite suggests critical melting, but the reported opx-out temperatures for lherzolite vary so much that it is not possible to determine the melting mode from the available experimental data. Since the compositions of the experimental Ca-rich melts approximate tholeiitic compositions it appears possible that the harzburgite was in equilibrium with a tholeiitic melt.

Accepting the generation of harzburgite by the extraction of a tholeiitic melt, the solidus curve for harzburgite indicates the maximum temperatures at which primary tholeiites may be generated. This relationship applies to both batch melting and critical melting. Experimental estimates of the MgO contents of melts generated in partially molten lherzolite are shown in Fig. 5 (*Kushiro, 1996; Hirose*

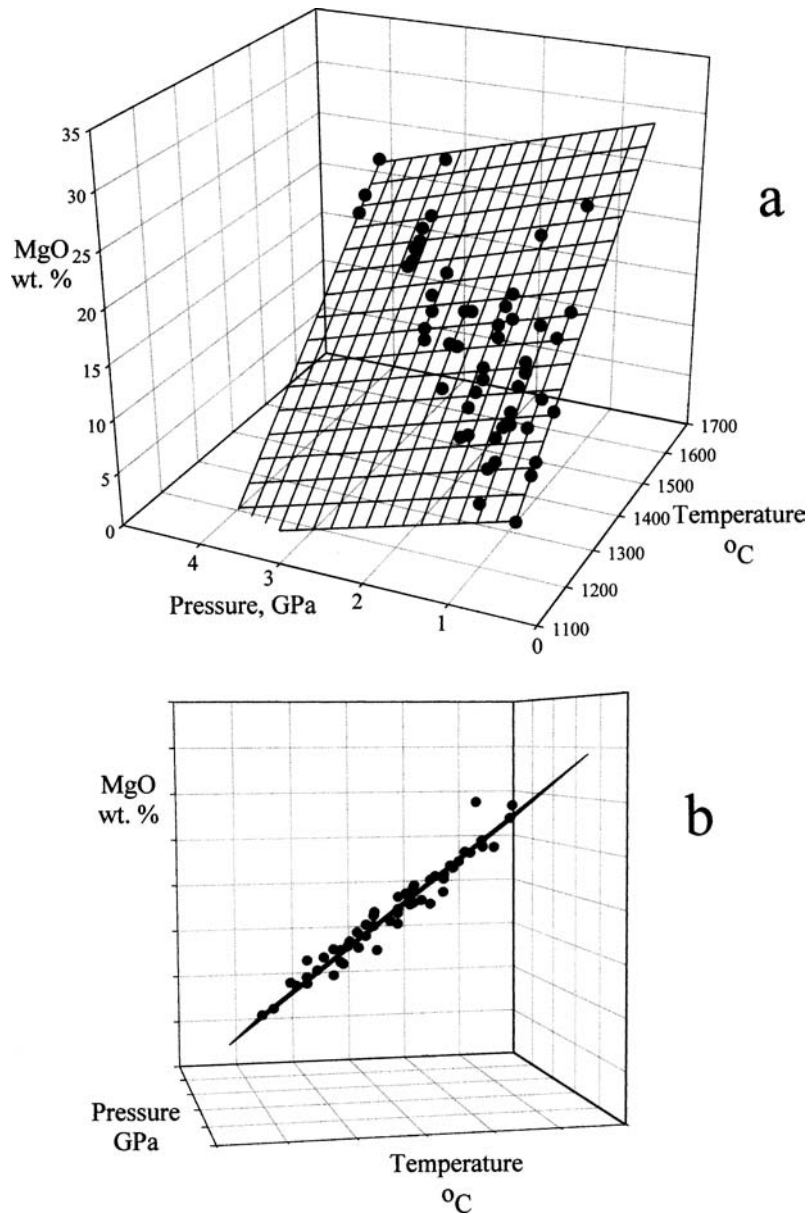


Fig. 5. **a** The dots show the MgO contents of glasses formed in partially molten lherzolitic compositions as a function of temperature and pressure (39.2 wt.% MgO: *Kushiro*, 1996; 37.2 wt.% MgO: *Hirose and Kushiro*, 1993; 37.3 wt.% MgO: *Walter*, 1998). The MgO contents display near-linear variations with both pressure and temperature, which allow to estimate the pressure-temperature dependence of the MgO by linear regression. **b** A view along the regression plane that shows the tight distribution of the points along this plane

and *Kushiro*, 1993; *Walter*, 1998). The data shown in Fig. 5 allow a linear regression analysis of the dependence of the MgO content of primary tholeiite as a function of both pressure (P in GPa) and temperature (T in °C):

$$\text{MgO wt.}\% = -49.63 - 2.11 * P + 0.0482 * T \quad (2\sigma = 0.94) \quad (1)$$

with a regression coefficient of 0.98. The fairly large regression coefficient shows that the experimental and analytical results are mutually consistent. The experimental melt compositions obtained by *Kushiro* (1996) also have SiO₂, Al₂O₃ and CaO well correlated with pressure and temperature. These oxides are not linearly correlated with pressure and temperature, but display maxima and minima. This equation may be used up to 200 to 300 °C above the lherzolite solidus (S, Fig. 2) given approximately by:

$$T\text{ }^{\circ}\text{C} = 1150 + 114.3 * P \quad (2)$$

The harzburgite solidus is given by:

$$T\text{ }^{\circ}\text{C} = 1380 + 82.9 * P \quad (3)$$

Using (1) and (3) the approximate MgO contents of primary tholeiite in equilibrium with harzburgite with 45 wt.% MgO can be estimated as a function of pressure:

$$\text{MgO wt.}\% = 16.89 + 1.88 * P \quad (4)$$

For pressures of 2.0 and 3.0 GPa, the maximal MgO contents are estimated to be 20.7 and 22.5 wt.% MgO, respectively. The liquidus temperature at 3.0 GPa is estimated as 1629 °C using Eq. (3), which is consistent with the liquidus temperature 1670 °C at 3.0 GPa, of a composition containing 24.6 wt.% MgO (*Ito and Kennedy*, 1968). A representative estimate of the average composition of the oceanic crust contains 17.8 wt.% MgO (*Elthon*, 1979). This estimate is considered to represent the minimum MgO content for a primary abyssal tholeiite, because the presence of tabular dunite bodies in the uppermost mantle section of ophiolite complexes show that the ascending tholeiitic magmas crystallized olivine before the magma intruded the oceanic crust (*Quick*, 1980; *Altbreksen et al.*, 1991). It should be mentioned that some authors have observed chemical and isotopic differences between ophiolite lavas and MORB, so that ophiolites may not represent typical oceanic crust formed at mid-oceanic ridges, but instead are formed in back arcs (*Miyashiro*, 1973; *Robinson et al.*, 1983; *Cameron*, 1985; *Matveev and Ballhaus*, 2002). A maximal MgO content of primary abyssal tholeiite within the range 21 to 23 wt.% MgO appears relevant. Such relatively high MgO contents for primary tholeiites was first suggested from phase relations by *O'Hara* (1968) and later by *Wright* (1971) for Hawaiian tholeiites, based on geochemical evidence.

The major element compositions of the melts extracted from the Horoman lherzolites must be situated somewhere along the extrapolated trend line for the lherzolites. A possible range of MgO contents may be estimated from the forsterite contents of the harzburgites, which are in the range Fo₉₀₋₉₂ (*Obata and Nishimoto*, 1992). Geochemical evidence suggests that partial melting of the Horoman peridotite took place near the garnet-spinel transition, starting within the garnet lherzolite field (*Frey et al.*, 1991; *Takazawa et al.*, 2000). Using the pressure dependent olivine-melt Fe-Mg partitioning relationship of *Ulmer* (1998), tholeiitic melts at 3.0 GPa with 18 and 22 wt.% MgO are in equilibrium with olivine containing Fo₉₀ and Fo_{91.6}, respectively. At 2.0 GPa the equivalent forsterite contents are Fo_{90.6} and Fo_{92.1}, respectively. A possible range of MgO contents for the extracted tholeiitic melts is therefore between 18 and 22 wt.% MgO. Similar MgO contents were

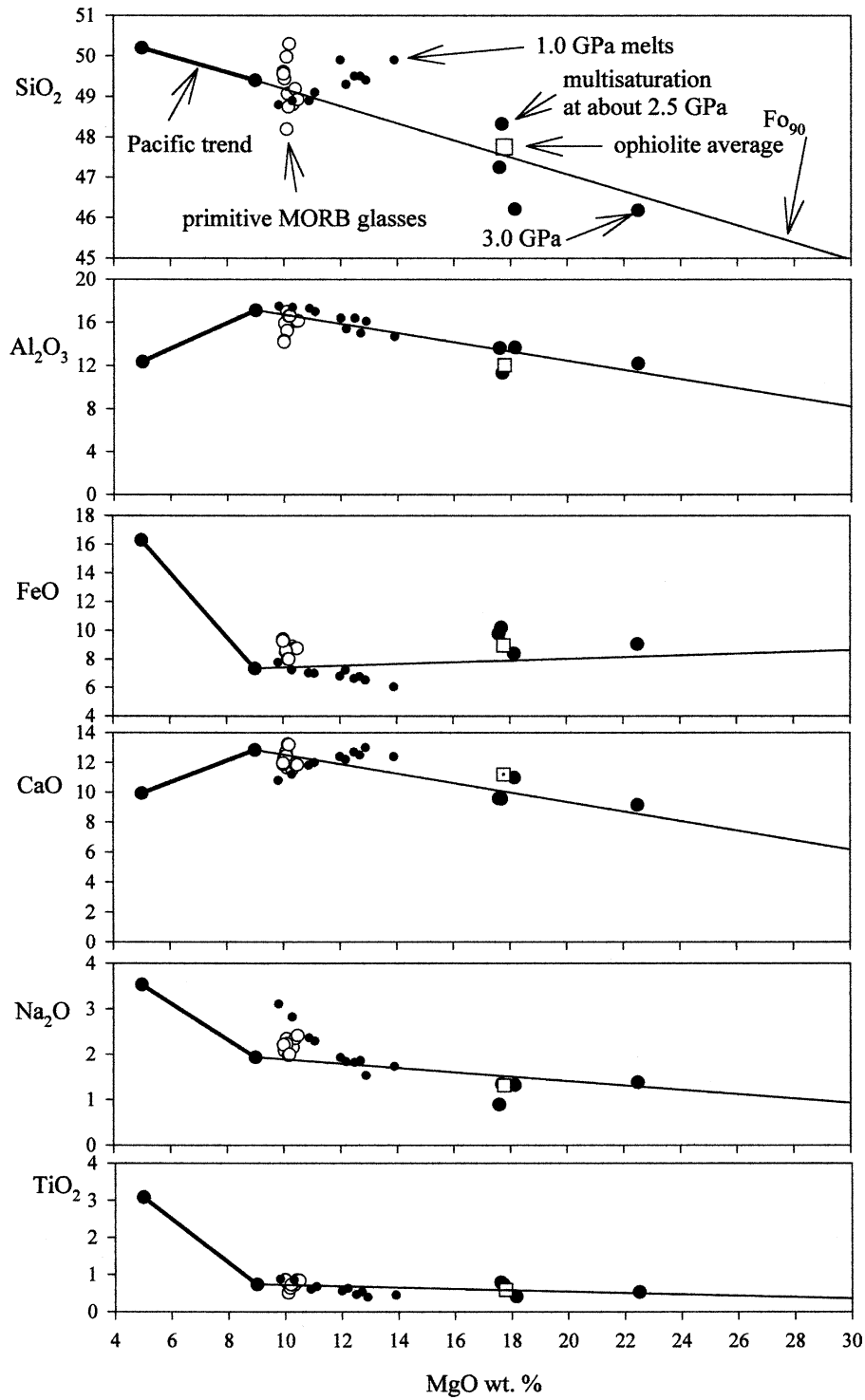
estimated for the extracted tholeiitic melt of the La Ronda massif (Frey et al., 1985).

The pressure-temperature phase relations of a dry abyssal tholeiitic composition with 17.6 wt.% MgO were studied experimentally by Elthon and Scarfe (1979; Table 1). Their tholeiitic composition is similar to an average estimate of the composition of the oceanic crust (Elthon, 1979; Table 1). The composition of the olivine phenocrysts in this lava is unknown, so the lava could either be a cumulate or an equilibrium composition. Elthon and Scarfe (1979) obtained multi-saturation with olivine, orthopyroxene, clinopyroxene, and garnet at 1460 °C and 2.5 GPa. This is about 30 °C above an average solidus of lherzolite according to the experimental results by Takahashi (1986), Kushiro (1996) and Walter (1998). According to the olivine-melt Fe–Mg partition relationship by Ulmer (1989) the forsterite content of olivine for this composition is Fo₉₀ at 2.5 GPa. A lherzolite containing 41 wt.% MgO has a molar Mg/(Mg + Fe) ratio of 0.9, suggesting an equilibrium olivine composition of Fo₉₀ (Maaløe and Aoki, 1977). The composition of the melt and the estimated pressure for multi-saturation is therefore consistent with the generation of the melt by partial melting of lherzolite. This result suggests that not all primary tholeiites leave behind harzburgitic residua.

The compositions of liquids coexisting with spinel lherzolite at 1.0 GPa was estimated by Fujii and Scarfe (1985). They obtained melts that contain between 9.8 and 12.9 wt.% MgO, and concluded that these melts may be primary compositions. However, melts with such low MgO contents cannot account for the composition of an average oceanic crust that contains about 18 wt.% MgO. Further, they concluded that the average composition of the oceanic crust determined by Elthon (1979) does not approach the composition of abyssal tholeiite by fractionation of olivine. It was shown by Maaløe and Steel (1980) that by fractionating Fo₉₀, this composition does indeed approach the composition of Pacific abyssal tholeiite with about 9 wt.% MgO (Fig. 6). At this MgO content the fractionate changes from olivine alone to olivine with clinopyroxene and plagioclase. Some ophiolite complexes like the Xigaze ophiolite, Tibet, show evidence for slow spreading, and lack the dunite layers at the bottom of the crust (Girardeau et al., 1985). A tholeiitic magma with 9 to 10 wt.% MgO can therefore be a primary magma for such ophiolites.

Depth and degree of partial melting are determined by the temperature of the upwelling mantle. There is no obvious reason why this temperature should be constant, so one should expect that the compositions of primary abyssal tholeiites

Fig. 6. Comparison between the trend for Pacific abyssal tholeiites (937 analyses; for compositions with 5 and 9 wt.% MgO see Table 1), primitive MORB glasses with more than 10 wt.% MgO, melts formed at 1.0 GPa, the composition of melts formed by multi-saturation at about 2.5 GPa, and an average estimate of the oceanic crust (Maaløe, 1979; Elthon, 1990; Fujii and Scarfe, 1985; Elthon and Scarfe, 1984; Maaløe and Jakobsson, 1980). The Fo₉₀ line shows the olivine control line for Pacific MORB with 9 wt.% MgO. The composition labelled 3.0 GPa contains 22.0 wt.% MgO and is estimated by adding olivine with Fo₉₁ to the average MORB composition with 17.8 wt.% MgO (Table 2). The MORB glasses, the 1.0 GPa melts, and the 2.5 and 3.0 GPa compositions plot near the olivine control line, suggesting that they may be primary



vary. It has often been assumed that the primary magma for abyssal tholeiite should have a constant composition, but this assumption implies a constant temperature for the upwelling mantle. The depth of onset of partial melting increases with

Table 2. *Compositions of abyssal tholeiite and harzburgite 62127*

	1	2	3	4	5	6	7	8
SiO ₂	50.20	49.40	49.25	47.76	49.33	47.25	46.88	43.30
Al ₂ O ₃	12.36	17.13	15.88	12.06	11.35	13.64	10.49	0.76
FeO	16.30	7.34	8.74	8.96	10.20	9.77	8.94	8.02
MgO	5.00	9.00	10.18	17.78	17.70	17.61	22.00	45.06
CaO	9.94	12.84	12.24	11.20	9.57	9.58	9.74	0.60
Na ₂ O	3.53	1.93	2.19	1.31	1.34	0.89	1.14	0.02
K ₂ O	0.24	0.10		0.03	0.11	0.06	0.03	–
MnO	0.07	0.09		0.12	0.17	0.14	0.10	0.13
TiO ₂	3.08	0.74	0.76	0.59	0.74	0.79	0.51	0.01
P ₂ O ₅	0.26	0.04			0.06		0.04	–
Sum	100.98	98.61	99.24	99.81	99.66	99.93	99.87	98.68

1 and 2: Pacific abyssal tholeiite with 5 and 9 wt.% MgO (*Maaløe*, 1979); 3: Average of primitive glasses with more than 10 wt.% MgO (*Elthon*, 1990); 4: Average of ophiolite complexes (*Elthon*, 1979); 5: Curacao tholeiite (*Beets et al.*, 1982); 6: Experimental multi-saturated tholeiite composition (*Elthon and Scarfe*, 1984); 7: Abyssal tholeiite containing 22.0 wt.% MgO; 8: Harzburgite 52127, the sum includes 0.457 wt.% Cr₂O₃ and 0.317 wt.% NiO (*Frey et al.*, 1991)

increasing temperature. A relatively high temperature of the upwelling mantle may result in a large spreading rate, so that the degree of melting increases with increasing spreading rate. A comparison between abyssal glass compositions and experimental melt compositions is shown in Fig. 6. The 1.0 GPa melt compositions were obtained for melts in equilibrium with a lherzolitic residuum between 1250 and 1310 °C (*Fujii and Scarfe*, 1985). The 1.0 GPa compositions plots near the primitive glass compositions obtained by *Elthon* (1990), suggesting that these glasses were generated at 1.0 GPa and about 1250 °C. The SiO₂ and CaO contents of these experimental melts increase with increasing temperature and form a trend that differs from the olivine-controlled abyssal trend. This evidence shows that an increasing degree of melting at 1.0 GPa cannot generate the MgO rich abyssal tholeiites. The latter may be formed at ≥ 2.5 GPa as shown by *Elthon* (1990). The phase volume of olivine contracts with increasing pressure, with the result that the melts become more MgO rich with increasing pressure (*Kushiro and Yoder*, 1974). In addition, the average composition of the oceanic crust is compared with the compositions of melts with multisaturation at about 2.5 GPa, and a composition is obtained by adding olivine to Pacific abyssal tholeiite with 9 wt.% MgO (Table 2). These various compositions tend to plot near the olivine control line for olivine with Fo₉₀.

Conclusions

The MgO contents of primary abyssal tholeiites leaving harzburgitic residua with 45 wt.% MgO are between 21 and 23 wt.% MgO, between 2.0 and 3.0 GPa pressure. Since harzburgite is the most depleted residuum, this range in MgO is the maximum possible range. Multisaturation with a lherzolitic residuum is obtained

for tholeiitic compositions with about 10 and 18 wt.% MgO. The possible MgO contents of primary abyssal tholeiite therefore appears to be within the range from 10 to 23 wt.% MgO. Considering that harzburgite has a frequent occurrence in the mantle sections of ophiolite complexes, MgO-rich primary tholeiites are probably prevalent.

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References

- Albrektsen BA, Furnes H, Pedersen RB* (1991) Formation of dunites in mantle tectonites, Leka ophiolite complex, Norway. *J Geodyn* 13: 205–220
- Baker MB, Beckett JR* (1999) The origin of abyssal peridotites: a reinterpretation of constraints based on primary bulk compositions. *Earth Planet Sci Lett* 171: 49–61
- Beets DJ, Klaver GT, Beunk FF, Kleft C, Maaskant P* (1982) Picrites as parental magma of MORB-type tholeiites. *Nature* 296: 341–343
- Boyd FR, England JL* (1963) Effect of pressure on the melting of enstatite. *Carnegie Inst Wash Yb* 62: 118–119
- Cameron WE* (1985) Petrology and origin of primitive lavas from the Troodos ophiolite complex, Cyprus. *Contrib Mineral Petrol* 89: 239–255
- Coleman RG* (1977) Ophiolites. Springer, Berlin Heidelberg New York
- Elthon D* (1979) High magnesia liquids as the parental magma for ocean floor basalts. *Nature* 278: 514–518
- Elthon D* (1990) The petrogenesis of primary mid-ocean ridge basalts. *Aquatic Sci* 2: 27–53
- Elthon D, Scarfe CM* (1984) High pressure phase equilibria of a high magnesia basalt and the genesis of primary oceanic basalts. *Am Mineral* 69: 1–15
- Frey FA, Rhodes JM* (1993) Intershield geochemical differences among Hawaiian volcanoes: implications for source compositions, melting processes and magma ascent paths. *Phil Trans Roy Soc Lond A* 342: 121–136
- Frey FA, Suen C, Stockman HW* (1985) The Ronda high temperature peridotite: geochemistry and petrogenesis. *Geochim Cosmochim Acta* 49: 2469–2491
- Frey FA, Shimizu N, Leinbach A, Obata M, Takazawa E* (1991) Compositional variations within the lower layered zone of the Horoman peridotite, Hokkaido, Japan: constraints on models for melt segregation. *J Petrol [Spec Vol]* 1991: 211–227
- Fujii T, Scarfe CM* (1985) Composition of liquids coexisting with spinel lherzolite at 10 kbar and the genesis of MORBs. *Contrib Mineral Petrol* 90: 18–28
- Garcia MO, Hulsebosch TP, Rhodes JM* (1995) Olivine-rich submarine basalts from the southwest rift zone of Mauna Loa volcano: implications for magmatic processes and geochemical evolution. *Geophys Monogr* 92: 219–239
- Girardeau J, Mercier JCC, Xibin W* (1985) Petrology of the mafic rocks of the Xigaze ophiolite, Tibet. *Contrib Mineral Petrol* 90: 309–321
- Hirose K, Kushiro I* (1993) Partial melting of dry peridotites at high pressures: determination of compositions of melts segregated from peridotite using aggregates of diamond. *Earth Planet Sci Lett* 114: 477–489

- Ito K, Kennedy GC* (1967) Melting and phase relations in a natural peridotite to 40 kilobars. *Am J Sci* 265: 519–538
- Ito K, Kennedy GC* (1968) Melting and phase relations in the plane tholeiite-lherzolite-nepheline basanite to 40 kilobars with geological implications. *Contrib Mineral Petrol* 19: 177–211
- Kushiro I* (1996) Partial melting of a fertile mantle peridotite at high pressures: an experimental study using aggregates of diamond. *Geophys Monogr* 95: 109–122
- Kushiro I, Yoder HS* (1974) Formation of eclogite from garnet lherzolite: liquidus relations in a portion of the system $\text{MgSiO}_3\text{--CaSiO}_3\text{--Al}_2\text{O}_3$ at high pressures. *Carnegie Inst Wash Yb* 73: 266–269
- Lippard SJ, Shelton AW, Gass IG* (1986) The ophiolite of northern Oman. *Mem Geol Soc Lond* 11: 178
- Maaløe S* (1979) Compositional range of primary tholeiitic magmas evaluated from major-element trends. *Lithos* 12: 59–72
- Maaløe S, Aoki K-I* (1977) The major element composition of the upper mantle estimated from the composition of lherzolites. *Contrib Mineral Petrol* 63: 161–173
- Maaløe S, Jakobsson SP* (1980) The PT phase relations of a primary oceanite from the Reykjanes peninsula, Iceland. *Lithos* 13: 237–246
- Maaløe S, Steel R* (1980) Mantle composition derived from the composition of lherzolites. *Nature* 285: 321–322
- Maaløe S, Tumyr O, James D* (1989) Population density and zoning of olivine phenocrysts in tholeiites from Kauai, Hawaii. *Contrib Mineral Petrol* 101: 176–186
- MacDonald GA, Katsura T* (1964) Chemical composition of Hawaiian lavas. *J Petrol* 5: 82–133
- Matveev S, Ballhaus C* (2002) Role of water in the origin of podiform chromite deposits. *Earth Planet Sci Lett* 203: 235–243
- Miyashiro A* (1973) The Troodos complex was probably formed at an island arc. *Earth Planet Sci Lett* 25: 217–222
- Mysen B, Kushiro I* (1977) Compositional variation of coexisting phases with degree of partial melting of peridotite in the upper mantle. *Am Mineral* 62: 843–865
- Nehru CE, Wyllie PJ* (1974) Electron microprobe measurements of pyroxene coexisting with H_2O undersaturated liquid in the join $\text{CaMgSi}_2\text{O}_6\text{--Mg}_2\text{Si}_2\text{O}_6\text{--H}_2\text{O}$ at 30 kilobars, with application to geothermometry. *Contrib Mineral Petrol* 48: 221–228
- Nui Y* (1997) Mantle melting and melt extraction processes beneath ocean ridges: evidence from abyssal peridotites. *J Petrol* 38: 1047–1074
- Obata M, Nishimoto H* (1992) Whole rock chemistry of the Horoman ultramafic rocks, Hokkaido, Japan. *Kumamoto J Sci Geol* 13: 25–36
- O'Hara MJ* (1968) The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks. *Earth Sci Rev* 4: 69–133
- O'Hara MJ, Yoder HS* (1967) Formation and fractionation of basic magma at high pressures. *Scot J Geol* 3: 67–117
- Paris JP* (1981) *Geologie de la Nouvelle-Caledonie, une essay de synthese*. Memoire du B.R.G.M. 113: 278 pp
- Quick JE* (1980) The origin and significance of large, tabular dunite bodies in the Trinity peridotite, northern California. *Contrib Mineral Petrol* 78: 413–422
- Rhodes JM* (1995) The 1852 and 1868 Mauna Loa picritic eruptions: clues to parental magma compositions and magmatic plumbing systems. *Geophys Monogr* 92: 241–262
- Rhodes JM* (1996) Geochemical stratigraphy of lava flows samples by the Hawaii Scientific Drilling Project. *J Geophys Res* 101: 11,729–11,746
- Robinson PT, Melson WG, O'Hearn, Schmincke HU* (1983) Volcanic glass compositions of the Troodos ophiolite, Cyprus. *Geology* 11: 4000–4004

- Robinson JAC, Wood BJ, Blundy JD* (1998) The beginning of melting of fertile and depleted peridotite at 1.5 GPa. *Earth Planet Sci Lett* 155: 97–111
- Roeder PL, Emslie RF* (1970) Olivine-liquid equilibrium. *Contrib Mineral Petrol* 29: 275–289
- Salters VJM, Longhi J* (1999) Trace element partitioning during the initial stages of melting beneath mid-ocean ridges. *Earth Planet Sci Lett* 166: 15–30
- Schwab BE, Johnston AD* (2001) Melting systematics of modally variable, compositionally intermediate peridotites and the effects of mineral fertility. *J Petrol* 42: 1789–1811
- Snow JE, Dick HJB* (1995) Pervasive magnesium loss by marine weathering of peridotite. *Geochim Cosmochim Acta* 59: 4219–4235
- Takahashi E* (1986) Melting of a dry peridotite KLB-1 up to 14 GPa: implications on the origin of peridotitic upper mantle. *J Geophys Res* 91: 9367–9382
- Takazawa E, Frey FA, Shimizu N, Obata M* (2000) Whole rock compositional variations in an upper mantle peridotite (Horoman, Hokkaido, Japan): are they consistent with a partial melting process? *Geochim Cosmochim Acta* 64: 695–716
- Ulmer P* (1989) The dependence of the Fe²⁺–Mg cation-partitioning between olivine and basaltic liquid on pressure, temperature and composition. *Contrib Mineral Petrol* 101: 261–273
- Walter MJ* (1998) Melting of garnet peridotite and the origin of komatiite and depleted lithosphere. *J Petrol* 39: 29–60
- Werner CD, Pilot J* (1997) Data report: Geochemistry and mineral chemistry of ultramafic rocks from the Kana area (Mark). *Proc Ocean Drill Prog Sci Rep* 153: 457–470
- Williams DW, Kennedy GC* (1969) Melting curve of diopside to 50 kilobars. *J Geophys Res* 74: 4359–4366
- Wright TL* (1971) Chemistry of Kilauea and Mauna Loa lava in space and time. *US Geol Surv Prof Pap* 735: 40pp
- Yoder HS* (1976) Generation of basaltic magma. National Academy of Sciences, Washington, 265 pp

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