

[3]

Melting relations of a magnesian abyssal tholeiite and the origin of MORBs

Toshitsugu Fujii¹ and Henri Bougault²

¹ *Geological Institute, University of Tokyo, Hongo, Tokyo 113 (Japan)*

² *Centre Oceanologique de Bretagne, B.P. 337, 29273 Brest, Cedex (France)*

Received February 18, 1982

Revised version received October 8, 1982

Melting relations of a glassy magnesian olivine tholeiite from the FAMOUS area have been studied within the pressure range 1 atm to 15 kbar. From 1 atm to 10 kbar, olivine is the liquidus phase, followed by plagioclase and Ca-rich clinopyroxene. Above 10 kbar, Ca-rich clinopyroxene appears on the liquidus, followed by orthopyroxene and spinel. Near 10 kbar, olivine, orthopyroxene, clinopyroxene, spinel and plagioclase crystallize within 10°C of the liquidus. This indicates that a liquid of this magnesian olivine tholeiite composition could coexist with mantle peridotite at about 10 kbar. This result is in agreement with the geochemistry of Ni; the Ni concentration of the studied sample corresponds to the theoretical concentration in a primary magma [14,15].

These data suggest that at least some magnesian mid-oceanic ridge basalts (MORBs) could be primary melts segregated from the mantle at depths near the transition zone between plagioclase lherzolite and spinel lherzolite (about 10 kbar). Based on this model, the residual mantle after extraction of MORBs should be lherzolite, not harzburgite.

High-pressure (7–10 kbar) fractionation models involving olivine, plagioclase and clinopyroxene, which have been proposed by several workers (e.g. [36]) to explain the varieties of MORBs, were re-emphasized based on this melting study. The rare occurrence of clinopyroxene as a phenocryst phase in MORBs is explained by precipitation in a magma chamber at high pressure, or by dissolution of clinopyroxene formed earlier at high pressure.

1. Introduction

The study of lavas that have been sampled by drilling or dredging of the sea floor has provided abundant evidence of the petrographic and chemical variations of mid-oceanic ridge basalts (MORBs). Present models for the origin of MORBs, however, may be divided into two groups.

The first is that all MORBs currently sampled are differentiated products of picritic magmas by substantial amounts of fractionation, mainly of olivine at pressures less than those at which the primary magmas were segregated from the mantle peridotite. O'Hara [1], who originally proposed this concept based on the analyses of phase diagrams of basaltic rocks [1,2], suggested the generation of picritic magmas at 25–30 kbar. Green et al.

[3] proposed the segregation of picritic primary magma at a pressure of 20 kbar based on the melting experiments of the composition of magnesian MORB + olivine. Stolper [4] also proposed picritic liquids as parents to MORBs and estimated that they segregated from the mantle at pressures of 15–20 kbar based on the equilibration experiments between basalt and harzburgite. Elthon and Scarfe [5–7] proposed that a primary magma is picritic and that it could be formed by the partial melting of garnet peridotite at 25 kbar.

The second is that some MORBs represent primary magmas formed by partial melting at shallow depths (25–30 km). Kushiro and Thompson [8] and Kushiro [9] suggested that one of the abyssal olivine tholeiites could be a primary magma generated at 7.5 kbar. Fujii et al. [10] also dis-

cussed the possibility that a slightly iron-enriched abyssal tholeiite might be a primary magma formed by the partial melting of plagioclase lherzolite at 8 kbar. Presnall et al. [11] proposed a model that magnesian abyssal tholeiites might be primary magmas generated at the cusp formed by the intersection of solidi of spinel lherzolite and plagioclase lherzolite (9.3 kbar) based on experiments in the system, CaO-MgO-Al₂O₃-SiO₂ (CMAS).

The second group also allows the possibility that picritic magmas formed at high pressures could be parental magmas to some MORBs; however, the first group tends to deny the possibility of magma generation at shallow depths. Most of the arguments by the first group are based on the spatial relationship between MORBs and the orthopyroxene field in the normative system; olivine, clinopyroxene, plagioclase and silica. By reducing the natural multi-component system to the normative four-component system, the original orthopyroxene field may be distorted to some extent in such a projection. There is no guarantee that the compositions of the liquids coexisting with olivine, orthopyroxene, clinopyroxene, and spinel or plagioclase are projected to a "point" or a "narrow" band in such a reduced system, as in the case of the simple four-component system, CMAS. This problem is also recognized by some of the first group [4,7]. They developed their discussions, however, assuming implicitly that the basaltic liquids coexisting with olivine, orthopyroxene and clinopyroxene (\pm spinel) at a pressure may be projected as a "point" or a "narrow band" in the above normative system. Because the magnesian MORBs are displaced from their "points" or "narrow bands" at any pressure, they deny the possibility that the magnesian MORBs could be primary magmas.

In this study, one of the most primitive MORBs based on both major and trace elements was selected for experimental study. This experimental study shows that the magnesian olivine tholeiite magma is multiply saturated with olivine, orthopyroxene, clinopyroxene and spinel or plagioclase at about 10 kbar. The results support the hypothesis that some magnesian MORBs represent primary magmas generated at about 10 kbar.

2. Starting material

The sample used in this study, ARP 74 10-16, is a glassy olivine tholeiite recovered from the Mont de Venus in the FAMOUS area [12,13]. It contains small amounts of olivine (Fo₈₉) and spinel ($\text{Cr}/(\text{Cr} + \text{Al} + \text{Fe}^{3+}) = 0.65$, $\text{Mg}/(\text{Mg} + \text{Fe}^{2+}) = 0.5$) which are less than 2 vol.%. More detailed descriptions of this rock are found in ARCYANA [12]. The sample is probably a representative of the lavas from the Mont de Venus or at least of a large part of this volcano in the FAMOUS area. Several samples which were recovered several hundreds of meters apart within the volcano show similar petrographical and chemical characteristics [12]. The chemical composition of CYP 31-35 [12,13] is cited as an example in Table 1.

In Table 1, the results of XRF analysis of ARP 74 10-16 (bulk rock and the separated matrix glass) and of microprobe analysis of the glass fused just above the liquidus at 10 kbar are shown. The presence of only small amounts of phenocryst minerals and the very close major element compositions of the bulk rock and of the separated matrix glass allow us to assume that the sample ARP 74 10-16 represents liquid composition. This assumption is also supported by the identical concentrations of some trace elements between the bulk rock and the separated matrix glass (Table 1). In this respect, Ni is useful because it is strongly partitioned in olivine. Any accumulation effect of olivine, therefore, would lead to a significant difference of the concentration of this element between the bulk rock and the matrix glass. A similar conclusion may be obtained from the Cr concentration with respect to the accumulation of spinel.

Bougault [14] and Sato [15] discussed the possible Ni contents in basaltic magmas formed by partial melting of peridotites and proposed that the concentration of Ni in a primary magma should be 214 ppm [14] or above 230 ppm [15]. They also showed that even a small extent of fractional crystallization of olivine causes significant decrease in Ni concentration. Based on this criterion, ARP 74 10-16 could be a primary magma [16].

On the basis of the chemical composition discussed above, it seems that ARP 74 10-16 may be

TABLE 1

Chemical data for starting material and the related rock (major elements in wt.%; trace elements in ppm)

	1	2	3	4	5
SiO ₂	50.0	50.26	49.47	49.81	49.57
TiO ₂	0.86	0.82	0.82	0.86	0.85
Al ₂ O ₃	15.5	15.05	15.23	15.13	15.26
Fe ₂ O ₃	–	0.84	0.97	0.93	1.06
FeO	8.05 ^a	7.28	7.28	7.33	7.33
MnO	0.17	0.14	0.14	0.14	0.14
MgO	10.5	10.13	10.66	10.43	10.63
CaO	12.2	12.09	12.21	12.23	12.11
Na ₂ O	2.10	2.07	1.94	2.20	2.11
K ₂ O	0.13	0.16	0.16	0.18	0.19
P ₂ O ₅	0.14	0.08	0.10	0.09	0.11
LOI ^b	–	0.09	0.02	0.09	0.10
LOI ^c	–	0.39	0.23	0.49	0.36
Total	99.7	99.40	99.23	99.91	99.82
Ni		240	247	253	255
Cr		625	626	645	628
Ta		0.48		0.49	0.52
Hf		1.32		1.31	1.32
Tb		0.43		0.40	0.42

1 = EPMA analysis of the glass fused at 10 kbar, 1300°C; 2 = bulk composition of ARP 74 10-16 (XRF) [12,13]; 3 = glass matrix of ARP 74 10-16 (XRF); 4 = bulk composition of CYP 31-35 (XRF) [12,13]; 5 = glass matrix of CYP 31-35 (XRF).

^a Total iron as FeO.

^b Loss on ignition at 110°C.

^c Loss on ignition at 1050°C.

considered to be one of the least fractionated and the least altered MORBs and can be a good candidate for a primary liquid.

3. Experiments

3.1. Experimental methods

The one atmosphere melting experiments were performed at $p_{O_2} = 10^{-8}$ bar with the Pt-loop method [10], where p_{O_2} was controlled by changing the mixing ratio of CO₂ and H₂ gases. Because the different p_{O_2} conditions do not change the crystallization sequence significantly except for the spinel phase in basaltic compositions [17], experiments were done only at the fixed p_{O_2} condition. In order to minimize iron loss, very thin Pt wire (0.05 mm) was used as a loop. The degree of iron loss from the Pt wire was estimated by analyzing

the glass by microprobe and it was found to be negligible if the glass beads are greater than 3 mm in diameter. All the runs were thus performed using glass beads greater than 3 mm in diameter.

The high-pressure melting experiments were carried out in graphite capsules in a solid-media apparatus [18] using the hot piston-out method without any friction correction. The powdered samples were heated at 1000°C at the QFM buffer for 24 hours and stored in an oven at 110°C. They were heated again in graphite capsules at about 1000°C for a minute just before the experiment in order to eliminate water. In the case of long duration runs (more than 5 hours), the graphite-lined, sealed Pt capsules were used. As mentioned below, the reducing condition of the graphite assembly caused some trouble in reproducibility of spinel crystallization. There were, in fact, small nickel metal blebs in a charge. The amount of iron alloying with the nickel metal, however, may be

TABLE 2A

Run data at 1 atm, $p_{O_2} = 10^{-8}$ bar

Run No.	T ($^{\circ}C$)	Time (hr)	Run products ^a
T1A	1290	5	gl
T3A	1285	5	gl
T2A	1280	5	gl + ol
T4A	1250	8.5	gl + ol
T6A	1240	10	gl + ol
T5A	1230	10	gl + ol + pl
T7A	1220	24	gl + ol + pl
T9A	1200	25	gl + ol + pl
T10A	1180	48	gl + ol + pl
T8A	1150	96	gl + ol + pl + cpx

^a gl = glass, ol = olivine, pl = plagioclase, cpx = clinopyroxene.

insignificant at the present experimental conditions. The microprobe analysis of glass fused at 10 kbar is almost identical with the XRF analysis (Table 1), indicating that iron loss by nickel metal is negligible. Temperature was measured by Pt/PtRh 10 thermocouples (short-duration runs) and by WRe5/WRe25 thermocouple (long-duration runs). No corrections were made for the effects of pressures on thermocouple emfs.

3.2. Experimental results

The results of melting experiments are summarized in Tables 2A and 2B, and Fig. 1. At low pressure (below 10 kbar) olivine is the liquidus

TABLE 2B

Run data at high pressure

Run No.	P (kbar)	T ($^{\circ}C$)	Run time (min)	Run products ^a
2105	7.5	1300	90	gl
T92	7.5	1290	120	gl + ol
2106	7.5	1275	120	gl + ol + pl
2101	7.5	1250	120	gl + ol + pl + cpx
T93	9	1290	120	gl + ol
T94	9	1280	120	gl + ol
T96	9	1280	240	gl + ol + pl
T2	10	1300	120	gl
T1	10	1290	60	gl + ol + cpx
T3	10	1290	240	gl + ol + cpx
T91	10	1290	540	gl + ol + cpx
2103	10	1275	120	gl + ol + cpx + opx
T89	10	1275	360	gl + ol + cpx + pl + opx(?)
2102	10	1250	90	gl + ol + cpx + opx(?)
T97	10	1250	360	gl + ol + cpx + pl + opx
T95	10.5	1290	120	gl + opx + cpx + sp
13L1	10.5	1290	2880	gl + opx + cpx
2108	11	1310	60	gl
T62	11	1300	240	gl + cpx + sp
T63	11	1290	240	gl + cpx + opx + sp
T61	12	1310	210	gl + cpx
2109	12	1300	120	gl + cpx + sp
T60	12	1280	240	gl + cpx + opx + sp
2100	15	1350	120	gl
2107	15	1325	180	gl + cpx
T4	15	1315	150	gl + cpx
2099	15	1300	120	gl + cpx

^a gl = glass, ol = olivine, pl = plagioclase, opx = orthopyroxene, cpx = clinopyroxene, sp = spinel.

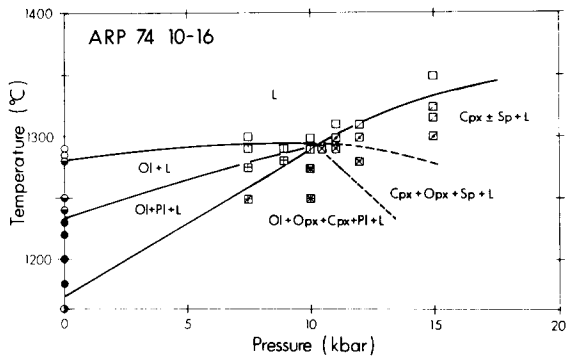


Fig. 1. Melting relations of ARP 74 10-16.

phase and followed by plagioclase and Ca-rich clinopyroxene. At pressures higher than 10 kbar, Ca-rich clinopyroxene appears on the liquidus instead of olivine. Orthopyroxene and spinel follow clinopyroxene. At about 10 kbar, olivine, clinopyroxene, orthopyroxene and plagioclase or spinel crystallize within 10°C below the liquidus, indicating that the composition of the liquid is close to the five-phase boundary of olivine, orthopyroxene, clinopyroxene, spinel and plagioclase. The compositions of minerals crystallized near the liquidus and of the coexisting liquid at about 10 kbar are shown in Table 3.

TABLE 3

Chemical compositions of the liquids and minerals near the liquidus around 10 kbar

	1	2	3	4	5	6
SiO ₂	40.8	50.0	53.7	52.5	49.8	49.1
TiO ₂	—	0.85	0.15	0.22	0.85	—
Al ₂ O ₃	0.10	16.0	4.12	5.52	15.7	32.3
Cr ₂ O ₃	0.08	0.04	0.48	0.57	0.04	—
FeO ^a	11.1	8.00	6.75	4.93	8.23	0.70
MnO	0.08	0.14	0.16	0.34	0.10	0.05
MgO	48.1	9.97	31.7	20.7	10.1	0.40
CaO	0.31	11.8	2.60	15.6	11.7	15.6
Na ₂ O	—	2.20	0.13	0.35	2.32	2.20
K ₂ O	—	0.12	—	—	0.13	—
P ₂ O ₅	—	0.14	—	—	0.13	—
Total	100.6	99.3	99.8	100.7	99.1	100.4
O	4.000		6.000	6.000		8.000
Si	1.000		1.880	1.874		2.240
Al	0.003		0.170	0.232		1.736
Ti	—		0.004	0.006		—
Cr	0.002		0.013	0.016		—
Fe ^a	0.227		0.198	0.147		0.027
Mn	0.002		0.005	0.010		0.002
Mg	1.757		1.654	1.101		0.027
Ca	0.008		0.097	0.597		0.762
Na	—		0.009	0.024		0.195
K	—		—	—		—
Total	2.998		4.029	4.008		4.989
Mg/(Mg + Fe ^a)	88.5	69.0	89.3	88.2	68.6	
Ca	0.4		5.0	32.3		Ca 79.7
Mg	88.2		84.9	59.7		Na 20.3
Fe ^a	11.4		10.1	8.0		K —

1 = olivine, 10 kbar, 1290°C, run No. T3; 2 = liquid, 10 kbar, 1290°C, run No. T3; 3 = orthopyroxene, 10.5 kbar, 1290°C, run No. 13L1; 4 = clinopyroxene, 10.5 kbar, 1290°C, run No. 13L1; 5 = liquid, 10.5 kbar, 1290°C, run No. 13L1; 6 = plagioclase, 7.5 kbar, 1250°C, run No. 2101.

^a All iron as Fe²⁺.

As shown in Table 2B, plagioclase sometimes failed to crystallize in short-duration runs as suggested by Bender et al. [19]. It is probably because the rates of nucleation and growth of plagioclase in basaltic melts are very small compared to other ferromagnesian minerals [20]. Because of this difficulty, microprobe analysis was successful only for plagioclase crystallized at 7.5 kbar and at 1250°C (Table 3). Orthopyroxene crystallized in short runs (120 minutes) were very small and hard to analyze with the microprobe without contamination from the basalt glass. In the 48-hour run at 10.5 kbar, however, orthopyroxene grew large enough (about 15 μm) to analyze without contamination by glass or clinopyroxene. Spinel crystallized with clinopyroxene is also normally too small to analyze with the microprobe. Spinel failed to crystallize in some runs. This may be due to the reducing condition in the graphite assembly.

4. Discussion

4.1. Primary magmas of MORBs

Analyses of the liquid coexisting with olivine and clinopyroxene, or orthopyroxene and clinopyroxene near the liquidus around 10 kbar (Table 3) are not far removed from the starting composition (Table 1). It indicates that the composition of ARP 74 10-16 is almost on the olivine-orthopyroxene-clinopyroxene cotectic, suggesting that it is a candidate primary magma formed by direct partial melting of mantle lherzolite. Crystallization of spinel and plagioclase at near-liquidus temperatures at about 10 kbar may indicate that the melting occurred around the solidus between the stability fields of plagioclase lherzolite and spinel lherzolite as proposed by Presnall et al. [11].

Different results, however, have been reported on basalts with compositions similar to this sample [3,19]. The principal difference in composition is the degree of silica saturation (or undersaturation). The analyses of the starting material in this study are located at the slightly more silica-rich side than those studied by Bender et al. [19], and Green et al. [3] in the normative projection [21] (Fig. 2).

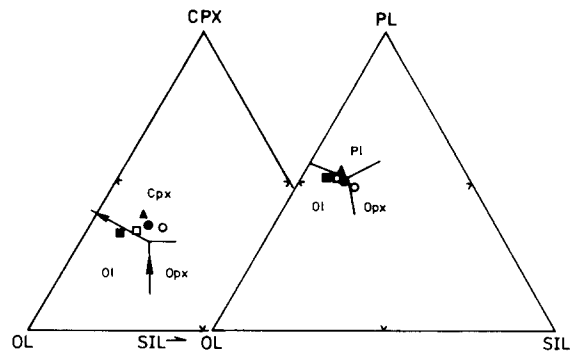


Fig. 2. Compositions of the magnesian MORBs which were used as starting materials in high-pressure melting studies. Left: projection from PL apex onto the plane, CPX-OL-SIL. Right: projection from CPX apex onto the plane, PL-OL-SIL. Projection methods are after Walker et al. [21]. Solid circle is microprobe analysis of the starting material of this study (ARP 74 10-16) on the glass fused just above the liquidus at 10 kbar. Open circle is XRF analysis of ARP 74 10-16 [12,13]. Solid square is microprobe analysis of the starting material (527-1-1) of Bender et al. [19]. Open square is bulk composition of 527-1-1 [27]. Solid triangle is starting material of Green et al. [13]. 10-kbar liquidus phase boundaries are from Stolper [4].

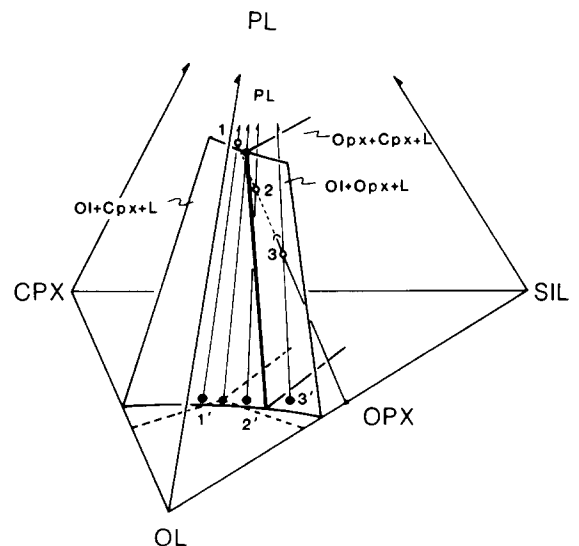


Fig. 3. A new interpretation of the results of the orthopyroxene-addition experiments by Green et al. [3] in the normative tetrahedron, PL-OL-CPX-SIL. Open circles are compositions studied by Green et al. [3]. Numbers 1, 2 and 3 are original composition and the compositions with 4 and 9 wt.% orthopyroxene added, respectively. Solid circles, 1', 2' and 3' are the projected points of 1, 2 and 3 onto the plane CPX-OL-SIL from the PL apex. Heavy solid line is the ol-opx-cpx cotectic.

This difference may partly explain the different results; orthopyroxene was found near the liquidus only in this study.

Bender et al. [19] found orthopyroxene only at 1310°C and 15 kbar, which is well below the clinopyroxene crystallization field. As long as clinopyroxene has no reaction relation with liquid, such a crystallization sequence is unlikely and their "orthopyroxene" may be a metastable phase, possibly caused by kinetic effects during their runs. Their observation of metastable (?) orthopyroxene, however, may suggest that the orthopyroxene field is not far removed from their chosen data point.

Green et al. [3] also performed melting experiments on a magnesian MORB. When they failed to crystallize orthopyroxene on the liquidus, they added enstatite or bronzite to their system. They had to add 9 wt.% of orthopyroxene before they found liquidus orthopyroxene. They claimed, thus, that orthopyroxene field is far from their starting composition and that the sample could not be a primary magma formed by partial melting of the upper mantle. Green et al. [3] made those additional runs only at 12 kbar. Their original data (unspiked with orthopyroxene) show that clinopyroxene is the liquidus phase at 12 kbar, indicating that a cotectic relationship of olivine and clinopyroxene occurs somewhere in the range 10–12 kbar. Therefore the cotectic relationship of olivine, orthopyroxene and clinopyroxene, if it occurs in their system, is expected to be at a lower pressure than 12 kbar, as is the case for the sample studied here. Since the boundary between the fields of clinopyroxene and clinopyroxene + orthopyroxene probably has a negative slope (Fig. 1), addition of orthopyroxene at a higher pressure than the cotectic would not prevent the crystallization of clinopyroxene until a fairly large amount of orthopyroxene had been added.

Based on the results of their orthopyroxene addition experiments, Stolper [4] interpreted that the ol-opx-cpx cotectic around 10 kbar exists far from the starting composition of Green et al. [3] (Fig. 2). The interpretation, however, is not a unique solution for the results by Green et al. [3]. As basalt is not a simple ternary system of olivine, orthopyroxene and clinopyroxene, caution must be exercised when we interpret the results of the

orthopyroxene-addition experiments.

An alternative interpretation of the results of the orthopyroxene-addition experiments [3] is schematically shown in the normative tetrahedron, PL-OL-CPX-SIL (Fig. 3). In the figure, open circle numbered 1 represents the original composition and those numbered 2 and 3 are compositions with additional orthopyroxene by 4 and 9%, respectively [3]. Although the natural system cannot be treated strictly as a four-component system [30,31], it was tentatively assumed that this normative system [21] could be treated as a four-component system in order to make discussion simple. This assumption may be justified if we restrict discussions on melts with fixed Fe/Mg ratio, Cr/Al ratio and constant alkali content because these constraints reduce the degrees of freedom of the system by three. Coexistence of olivine, orthopyroxene, clinopyroxene and liquid (the ol-opx-cpx cotectic) is, therefore, isobarically univariant. The ol-opx-cpx cotectic, thus, must be projected as a line in the diagram (heavy solid line). As far as the slope of the divariant plane (opx + cpx + liq) is steeper than the orthopyroxene-addition line, we are quite free to select the position of the cotectic line in order to explain the results of Green et al. [3]. In Fig. 3, the divariant plane crosses the orthopyroxene-addition line between 2 and 3; thus the compositions 1 and 2 are within the cpx field. The invariant point (ol + opx + cpx + sp + liq) could be close to the original composition of Green et al. [3] as shown in Fig. 3. The new interpretation is not inconsistent with the systematic increase of liquidus temperature with addition of orthopyroxene [3]. The relationship between the liquidus phase boundaries and the compositions projected from the PL apex onto the plane CPX-OL-SIL is schematically shown in Fig. 3 and also shown in Fig. 4A based on the projection method of Walker et al. [21]. In Fig. 4A, heavy solid line represents the ol-opx-cpx cotectic and the light solid lines and the broken lines are liquidus phase boundaries of spinel saturation and of CPX-OL-SIL plane, respectively. The difference of interpretation between Stolper [4] and this study is shown in Fig. 4B. As is clear from these figures, the orthopyroxene liquidus field may not be properly described in the phase diagram of Stolper [4]. Therefore, the

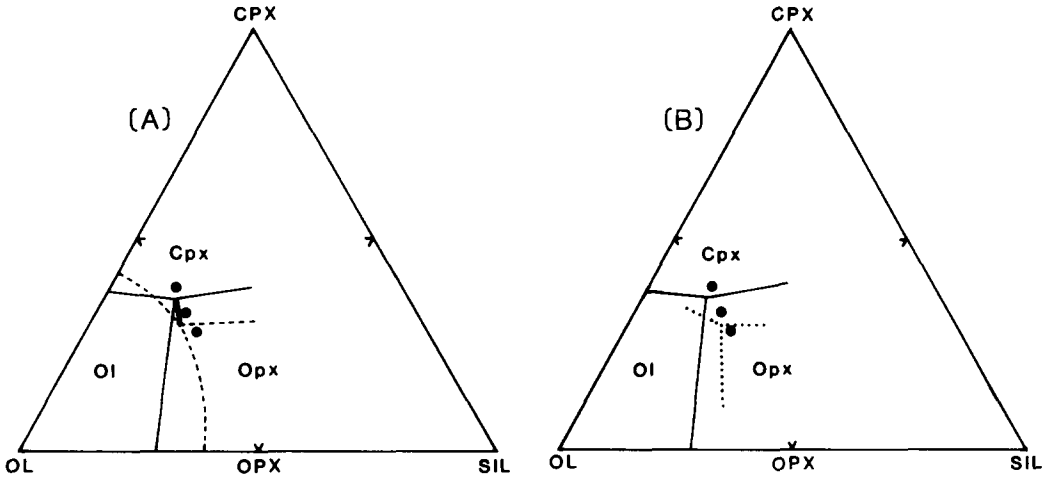


Fig. 4. Projection from the PL apex onto the plane CPX-OL-SIL. A. Liquidus phase boundaries based on the new interpretation (Fig. 3) of the results of the orthopyroxene-addition experiments by Green et al. [3]. Solid circles are compositions studied by Green et al. [3]. Heavy solid line is the ol-opx-cpx cotectic. Light solid lines are the liquidus phase boundaries of spinel saturation. Dashed lines are the liquidus phase boundaries on the plane CPX-OL-SIL. B. Comparison of the liquidus boundaries. Solid lines are the boundaries based on the new interpretation (Fig. 3). Dotted lines are those of Stolper [4].

results of the orthopyroxene-addition experiments at 12 kbar by Green et al. [3] may not be definitive enough to declare that their original composition is far from the orthopyroxene field at any pressure. Considering that their composition is not so different from that of this study (Fig. 2), it is possible that their composition may also be saturated in orthopyroxene around 10 kbar.

O'Hara [1] argued that MORBs are not primary magmas because their compositions do not intersect the primary phase field of orthopyroxene at any pressure. Therefore, he argued, MORBs could not represent primary magmas derived from an upper mantle containing olivine and orthopyroxene. However, it is obvious from the present study that at least one magnesian MORB intersects the primary phase field of orthopyroxene around 10 kbar and that the location of the orthopyroxene field proposed by O'Hara [1] is not correct.

When Kushiro and Thompson [8] reported a Ca-poor pyroxene at the liquidus of a less magnesian MORB (T-87) at about 7.5 kbar and suggested that the basalt may be a primary magma of MORBs, O'Hara [22] argued that the Ca-poor pyroxene was too calcic ($\text{CaSiO}_3 = 8.9 \text{ mol.}\%$) to be an orthopyroxene and that, because it was too

enriched in iron ($\text{Mg}/(\text{Mg} + \text{Fe}) = 0.84$), T-87 could not coexist with upper mantle peridotite. The chemical composition of Ca-poor pyroxene published by Kushiro and Thompson [8] is, in fact, far from orthopyroxene. The high $\text{Ca}/(\text{Ca} + \text{Mg} + \text{Fe})$ and Fe/Mg ratio may be due to contamination by coexisting basalt glass during microprobe analyses. As mentioned above, in runs of short duration, orthopyroxene does not grow large enough to be analyzed with the microprobe without contamination by basalt glass. According to Ross and Huebner [23], the stability of magnesian pigeonite ($\text{Mg}/(\text{Mg} + \text{Fe}) > 0.8$) is above 1250°C at low pressures. Lindsley [24] suggested that the minimum temperature of pigeonite stability at 10 kbar is about 100°C higher than that at 1 atm. These results indicate that the stability of pigeonite around 10 kbar is above 1300°C ; therefore the Ca-poor pyroxene reported by Kushiro and Thompson [8] is probably orthopyroxene rather than pigeonite. Fujii et al. [10] also reported that one of the abyssal tholeiites from DSDP Leg 45 is saturated with olivine, orthopyroxene, clinopyroxene and plagioclase at about 8 kbar. These results suggest that some MORBs, not only the extremely magnesian MORB in this study but also

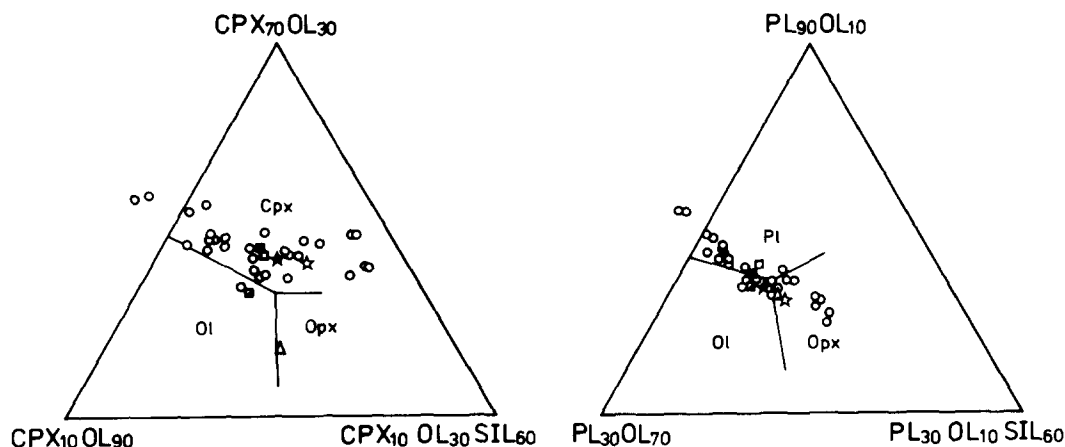


Fig. 5. Compositions of magnesian MORBs. A. Projection from PL apex onto the plane, CPX-OL-SIL ($CPX_{70}OL_{30}$ - $CPX_{10}OL_{90}$ - $CPX_{10}OL_{30}SIL_{60}$). B. Projection from CPX apex onto the plane PL-OL-SIL ($PL_{90}OL_{10}$ - $PL_{30}OL_{70}$ - $PL_{30}OL_{10}SIL_{60}$). Circles are magnesian MORB glasses ($FeO/MgO < 0.96$) from the FAMOUS area [25,26]. Stars indicate composition of starting material in this study (solid star; microprobe analysis, open star; XRF analysis). Squares are microprobe analyses of glass from a sample, ALV-519-4-1 (open square is from Langmuir et al. [27], solid square is from Stolper [4] and half-solid square is from Bryan and Moore [25]. Triangle indicates the "pseudo-invariant" composition at 10 kbar by Elthon and Scarfe [7]. Solid lines are 10-kbar liquidus phase boundaries by Stolper [4].

slightly iron-rich MORBs, could be formed by the partial melting of plagioclase lherzolite or spinel lherzolite at pressures of 7–10 kbar.

Stolper [4] performed equilibration experiments between a magnesian MORB and a harzburgite at high pressures, and studied the compositions of the liquid that coexists with olivine and orthopyroxene \pm clinopyroxene. Combining the results with melting studies of basalts [3,8,10,19], he estimated the ol-opx-cpx cotectic "point" within the OL-PL-CPX-SIL diagram [21] at pressures between 10 and 20 kbar. Based on the results, he discussed that, although the ol-opx-cpx cotectic approaches the MORB cluster at slightly less than 10 kbar, these MORBs of that location are moderately enriched in iron and titanium and that the primitive (magnesian) MORBs are significantly displaced from his ol-opx-cpx cotectic at any pressure. He argued, thus, that magnesian MORBs cannot be primary magmas.

It is shown above, however, that the orthopyroxene field may not be properly described in the diagram of Stolper [4]. Also it should be noted that interlaboratory discrepancies of microprobe analyses as shown by the analyses of ALV-519-4-1 [4,25,27] in Fig. 5 are large in this kind of projec-

tion and thus caution must be exercised when we discuss small displacement of points within the normative diagram. Considering this and the evidence that the sample in this study is saturated in olivine, orthopyroxene, clinopyroxene and spinel (\pm plagioclase) at 10 kbar, some magnesian MORBs plotted near the sample studied here in Fig. 5 can be primary magmas.

Presnall et al. [11], Presnall and Hoover [28] and Elthon [29] have discussed that the elongation of the MORBs cluster toward silica poor end shown in Fig. 5 reflects analytical uncertainty, especially Na_2O and SiO_2 . If the points plotting at the silica poor end of the cluster did so because of this effect, most of the magnesian MORBs could be formed by the partial melting of lherzolite at about 10 kbar. Stolper [4] argued, however, that many of the compositions plotting at the silica poor end of the cluster are properly located. If these compositions are properly located as Stolper [4] mentioned, this undermines the statement made above that most of the magnesian MORBs are primary magmas formed at about 10 kbar. About half of the magnesian MORBs in Fig. 5, which are located at the silica-poor side of the composition of the sample in this study, may not be formed by

partial melting of the mantle peridotite.

As discussed above and also mentioned by Bryan and Dick [30], however, the ol-opx-cpx cotectic is not isobarically invariant not only in natural system but also even in the CMAS system. It is not well understood how large an area the ol-opx-cpx cotectic or the ol-opx-cpx-sp (or pl) cotectic in the natural basaltic system occupy in the normative projection methods proposed by Walker et al. [21] or Presnall et al. [11]. It is reported by Fujii and Scarfe [31], however, that the compositions of basaltic liquid coexisting with natural magnesian olivine, orthopyroxene, clinopyroxene and spinel at 10 kbar, occupy a large area in the projection method by Walker et al. [21]. They discussed that there is overlap between their compositions and magnesian MORBs. This may indicate that most of the magnesian MORBs can be generated by the partial melting of lherzolite around the pressure of 10 kbar, which is contrary to the conclusion made by Stolper [4].

Elthon and Scarfe [7] also claimed, based on the melting experiments of picrite, that the location of the ol-opx-cpx-sp cotectic ("pseudo-invariant point") is far from any magnesian MORB and thus most MORBs represent differentiated magmas rather than primary magmas. Their "pseudo-invariant point" at 10 kbar was also plotted in Fig. 5. Their "point" is, in fact, completely displaced from the cluster for magnesian MORBs. However, it must be kept in mind that the composition of the liquid which coexists with olivine, orthopyroxene, clinopyroxene and spinel at 10 kbar in the experiment of Elthon and Scarfe [7] is fairly iron-rich (coexisting olivine is $Fe_{0.83}$). As discussed before, the normative system, OL-CPX-PL-SIL, can be treated as a four-component system only when the Fe/Mg ratio, Cr/Al ratio and alkali content of the melt are fixed. The coexistence of five phases (ol, opx, cpx, sp and liq) is no longer isobarically invariant unless the Fe/Mg ratio of the melt is fixed. The effect of iron-substitution for magnesium on the phase boundaries in this kind of projection is not known. It may not be adequate, therefore, to include such an iron-rich melt when we discuss the genesis of magnesian MORBs.

Based on the melting experiments of peridotite-40% olivine compositions, Jaques and

Green [32] argued that partial melting of peridotites around 10 kbar produces liquids of olivine tholeiite composition but that those liquids do not resemble MORBs because their Al_2O_3 contents ($\leq 14.5\%$) are much lower than those of MORBs (15–17%). Their results, however, indicate that the Al_2O_3 content of the liquid shows a good correlation with the Al/(Al + Cr) ratio of coexisting spinel and thus the Al_2O_3 content of partial melt depends on the composition of spinel near the solidus of peridotite. It seems possible, therefore, to produce high-alumina olivine tholeiite (MORBs) by partial melting of spinel peridotite, similar in composition to pyrolite except for its spinel composition. Thus, the experiments of Jaques and Green [32] do not provide new evidence for the model which suggests MORBs are not primary magmas.

It is, therefore, possible that at least some MORBs and probably many magnesian MORBs including the olivine tholeiite studied here, represent primary magmas derived by the partial melting of the oceanic upper mantle leaving lherzolite as a residue. The depths of segregation from the mantle could be near the transition zone between plagioclase lherzolite and spinel lherzolite (about 10 kbar) as proposed by Presnall et al. [11].

4.2. Fractionation of MORBs

It is commonly discussed that because the composition of MORBs are distributed along the 1-atm cotectics of olivine, clinopyroxene and plagioclase [4,21,25,26], most MORBs have undergone low-pressure fractionation by separation of olivine, clinopyroxene and plagioclase [4,21]. Attempt to relate each composition by fractional crystallization of these three phases lead to the conclusion that the role of clinopyroxene and plagioclase are significant and that of olivine is subordinate and sometimes negative (dissolution of olivine) even in a trial to relate magnesian olivine tholeiite to less magnesian olivine tholeiite [26,33]. This fact conflicts with the petrography of MORBs (e.g. [26]). Most MORBs, except for fairly iron- and titanium-enriched ones, are olivine- and/or plagioclase-phyric and it is only very rarely that clinopyroxene occurs as phenocrysts (e.g. [26]). In order

to explain this feature, Bryan [26] proposed a model in which clinopyroxene crystallizes under volatile enriched conditions and then it dissolves in contact with hotter, dry magma. The measurements of water content in the glass matrix of magnesian MORBs [34,46], however, suggest that the concentration of water in the magma is not especially high (about 0.2 wt.%). It is unlikely, therefore, that such a small amount of volatile component had a significant role in the evolution of MORBs [11,30].

As shown in Fig. 1 and also shown by previous workers both in the CMAS system [11,35] and in the natural system [8–10,19], the clinopyroxene field expands relative to those of olivine and plagioclase with increasing of pressure for various compositions of MORBs. The possibility of three phase fractionation (olivine, clinopyroxene and plagioclase) without significant subtraction of olivine is much higher at high pressures [10,19,36–38]. Magnesian olivine tholeiite magma formed by direct partial melting of lherzolite around 10 kbar may separate from the residual lherzolite and form a magma chamber at slightly shallower depths. As the magma chamber is still at high pressure, crystallization of clinopyroxene and plagioclase would immediately follow olivine (Fig. 1). Plagioclase might float to the upper portion of the magma chamber [10,38,39], and olivine and clinopyroxene might settle forming wehrlite cumulate at the bottom (e.g. [19,38]).

The magma fractionated in the high-pressure magma chamber might crystallize olivine or olivine and plagioclase again but no more clinopyroxene when it migrates towards the surface, because the expansion of the olivine or olivine + plagioclase fields relative to the clinopyroxene field become larger with decreasing pressure even in iron-enriched magma [8,10]. If the high pressure phenocrysts such as olivine, clinopyroxene and plagioclase were carried near the surface, olivine and plagioclase may dissolve initially but be followed shortly by further crystallization. Clinopyroxene, however, would continue to dissolve [36] because of the reason described above. Some magnesian clinopyroxene phenocrysts found rarely in magnesian MORBs [25,26,40,41] could be relicts of these dissolved high pressure clinopyroxene [19]. If the

magma, which is enriched in the floated plagioclase phenocrysts in the upper portion of the magma chamber, ascends to lower pressure, it would crystallize olivine and the accumulated plagioclase may dissolve [38,39]. In this way olivine-plagioclase-phyric basalt with corroded plagioclase phenocrysts [45] may form [38,39]. It is often shown that the core composition of such corroded plagioclase is calcic (An_{72} to An_{88}) [43,45]. The analyzed composition of plagioclase crystallized at 7.5 kbar (Table 3) is within the range, but not so calcic as the extreme example. Considering that the analyzed plagioclase is coexisting with clinopyroxene (Table 2B), the composition of the plagioclase immediately after the crystallization of olivine could be more calcic. Another study [19], however, suggests that the first formed plagioclase becomes more sodic with an increase of pressure. Further studies on the composition of plagioclase crystallized at high pressure are, therefore, necessary. If the primary magma ascends to the surface directly, it would form aphyric or sparsely phyric magnesian olivine tholeiite such as that studied here. If it forms a shallow magma chamber, it would crystallize olivine followed by plagioclase. Clinopyroxene may crystallize after the magma becomes largely fractionated.

Similar models have been proposed by several workers (e.g. [36–38]). This scenario may be too simplified and more complicated processes such as mixing of fractionated magma with relatively fresh magma [42,43,45] probably take place; however, this scenario seems to explain the scarcity of clinopyroxene phenocrysts in MORBs in spite of the significance of clinopyroxene fractionation. Fisk and Bence [44] also proposed a high-pressure fractionation model based on the analyses of spinel within magnesian MORBs and the experiments at 1 atm.

5. Conclusion

The studied sample, ARP 74 10-16, could coexist with mantle peridotite at about 10 kbar, indicating that it is a possible candidate for a primary magma. Crystallization of spinel or plagioclase at near-liquidus temperatures at about 10 kbar may indi-

cate that the melting occurred around the solidus between the stability fields of plagioclase lherzolite and spinel lherzolite, supporting the model proposed by Presnall et al. [11]. This result is in agreement with the previous conclusions obtained from the geochemical studies on the MORBs of similar compositions (e.g. [16]).

The model of high-pressure fractionation proposed by several workers (e.g. [36]) was re-emphasized based on this melting study. It explains the scarcity of clinopyroxene phenocrysts in MORBs in spite of the significance of clinopyroxene fractionation which is supposed from geochemical studies of MORBs.

Acknowledgements

The experimental work was performed at the Geological Institute, University of Tokyo. The manuscript was written when one of the authors (T.F.) stayed in the experimental Petrology Laboratory, Department of Geology, University of Alberta. I. Kushiro is thanked for his continued interest and his discussion. C.M. Scarfe is thanked for his discussion and the critical review of the manuscript. H. Fukuyama, D.M. Harris and M. Brearley are also thanked for the review. Two anonymous reviewers provided constructive comments.

References

- 1 M.J. O'Hara, Are ocean floor basalts primary magma?, *Nature* 220 (1968) 683–686.
- 2 M.J. O'Hara, Primary magmas and the origin of basalts, *Scot. J. Geol.* 1 (1965) 19–40.
- 3 D.H. Green, W.O. Hibberson and A.L. Jaques, Petrogenesis of mid-ocean ridge basalts, in: *The Earth: Its Origin, Structure and Evolution*, M.W. McElhinny, ed. (Academic Press, London 1979) 265–299.
- 4 E. Stolper, A. Phase diagram for mid-ocean ridge basalts: preliminary results and implications for petrogenesis, *Contrib. Mineral. Petrol.* 74 (1980) 13–27.
- 5 D. Elthon and C.M. Scarfe, High-pressure phase equilibria of a high-magnesia basalt: implications for the origin of mid-ocean ridge basalts, *Carnegie Inst. Washington, Yearb.* 79 (1980) 277–281.
- 6 D. Elthon and C.M. Scarfe, High-pressure phase equilibria of a high-magnesia basalt and the genesis of primary oceanic basalts: implications for the origin of mid-ocean ridge basalts, *Geol. Soc. Am., Abstr. Prog.* 12 (1980) 421.
- 7 D. Elthon and C.M. Scarfe, High-pressure phase equilibria of a high-magnesia basalt and the genesis of primary oceanic basalts, *Am. Mineral.* (in press).
- 8 I. Kushiro and R.N. Thompson, Origin of some abyssal tholeiites from the Mid-Atlantic Ridge, *Carnegie Inst. Washington, Yearb.* 71 (1972) 403–406.
- 9 I. Kushiro, Origin of some magmas in oceanic and circum-oceanic regions, *Tectonophysics* 17 (1973) 211–222.
- 10 T. Fujii, I. Kushiro and M. Hamuro, Melting relations and viscosity of an olivine tholeiite, in: W.G. Melson, P.D. Rabinowitz et al., *Initial Reports of the Deep Sea Drilling Project*, 45 (U.S. Government Printing Office, Washington, D.C., 1978) 513–517.
- 11 D.C. Presnall, J.R. Dixon, T.H. O'Donnell and S.A. Dixon, Generation of mid-ocean ridge tholeiites, *J. Petrol.* 20 (1979) 3–35.
- 12 ARCYANA, Rocks collected by bathyscaph and diving saucer in the FAMOUS area of the Mid-Atlantic Rift Valley: petrological diversity and structural setting, *Deep-Sea Res.* 24 (1977) 565–589.
- 13 H. Bougault, P. Cambon, O. Corre, J.L. Joron and M. Treuil, Evidence for variability for magmatic processes and upper mantle heterogeneity in the axial region of the Mid-Atlantic Ridge near 22°N and 36°N, *Tectonophysics* 55 (1979) 11–34.
- 14 H. Bougault, Evidence de la cristallisation fractionnée au niveau d'une ride médio-océanique: Co, Ni, Cr. FAMOUS, Leg 37 du D.S.D.P., *Bull. Soc. Géol. Fr.* XIX (1977) 1207–1212.
- 15 H. Sato, Nickel content of basaltic magmas as a measure of the degree of olivine fractionation, *Lithos* 10 (1977) 113–120.
- 16 H. Bougault, J.L. Joron and M. Treuil, Alteration, fractional crystallization, partial melting, mantle properties from trace elements in basalts recovered in the north atlantic, in: *Deep Drilling Results in the Atlantic Ocean: Ocean Crust*, Am. Geophys. Union, Maurice Ewing Ser. 2 (1979) 352–368.
- 17 H. Fukuyama and K. Hamuro, Melting relations of Leg 46 basalts at atmospheric pressure, in: L. Dmitriev, J. Heirtzler et al., *Initial Reports of the Deep Sea Drilling Project*, 46 (U.S. Government Printing Office, Washington, D.C., 1978) 235–239.
- 18 F.R. Boyd and J.L. England, Apparatus for phase equilibrium experiments at pressures up to 50 kbars and temperatures up to 1750°C, *J. Geophys. Res.* 65 (1960) 741–748.
- 19 J.F. Bender, F.N. Hodges and A.E. Bence, Petrogenesis of basalts from the project FAMOUS area: experimental study from 0 to 15 kbars, *Earth Planet. Sci. Lett.* 41 (1978) 277–302.
- 20 C.H. Donaldson, An experimental investigation of the delay in nucleation of olivine in mafic magmas, *Contrib. Mineral. Petrol.* 69 (1979) 21–32.
- 21 D. Walker, T. Shibata, S.E. Delong, Abyssal tholeiites from the Oceanographer Fracture Zone II. Phase equilibria and mixing, *Contrib. Mineral. Petrol.* 70 (1979) 111–125.
- 22 M.J. O'Hara, Non-primary magmas and dubious mantle plume beneath Iceland, *Nature* 243 (1973) 507–508.

- 23 M. Ross and J.S. Huebner, Temperature-composition relationships between naturally occurring augite, pigeonite, and orthopyroxene at one bar pressure, *Am. Mineral.* 64 (1979) 1133–1155.
- 24 D.H. Lindsley, Phase equilibria of pyroxenes at pressures > 1 atmosphere, in: *Reviews in Mineralogy: Pyroxenes*, C.T. Prewitt, ed. (1980) 289–307.
- 25 W.B. Bryan and J.G. Moore, Compositional variations of young basalts in the Mid-Atlantic Ridge rift valley near lat. 36°49'N, *Geol. Soc. Am. Bull.* 88 (1977) 556–570.
- 26 W.B. Bryan, Regional variation and petrogenesis of basalt glasses from the FAMOUS area, Mid-Atlantic Ridge, *J. Petrol.* 20 (1979) 293–325.
- 27 C.H. Langmuir, J.F. Bender, A.E. Bence, G.N. Hanson and S.R. Taylor, Petrogenesis of basalts from the FAMOUS area, Mid-Atlantic Ridge, *Earth Planet. Sci. Lett.* 36 (1977) 133–156.
- 28 D.C. Presnall and J.D. Hoover, Analytical uncertainties and the problem of picritic versus tholeiitic primary magmas at mid-ocean ridges, *Geol. Soc. Am., Abstr. Prog.* 13 (1981) 533.
- 29 D. Elthon, Isomolar versus isostructural pseudo-liquidus phase diagrams for oceanic basalts, *Am. Mineral.* (in press).
- 30 W.B. Bryan and H.J.B. Dick, Contrasted abyssal basalt liquidus trends: evidence for mantle major element heterogeneity, *Earth Planet. Sci. Lett.* 58 (1982) 15–26.
- 31 T. Fujii and C.M. Scarfe, Partial melting of spinel lherzolite and its bearing on the origin of MORBs, *Geol. Soc. Am., Abstr. Prog.* 13 (1981) 456.
- 32 A.L. Jaques and D.H. Green, Anhydrous melting of peridotite at 0–15 kb pressure and the genesis of tholeiitic basalts, *Contrib. Mineral. Petrol.* 73 (1980) 287–310.
- 33 A.P. le Roex, A.J. Erlank and H.D. Needham, Geochemical and mineralogical evidence for the occurrence of at least three distinct magma types in the “FAMOUS” region, *Contrib. Mineral. Petrol.* 77 (1981) 24–37.
- 34 E. Ito, A.T. Anderson, Jr. and D.M. Harris, Alteration of oceanic crust and geologic cycling of chlorine and water (submitted to *Geochim. Cosmochim. Acta*).
- 35 D.C. Presnall, S.A. Dixon, J.R. Dixon, T.H. O'Donnell, N.L. Brenner, R.L. Schrock and D.W. Dycus, Liquidus phase relations on the join diopside-forsterite-anorthite from 1 atm to 20 kbar: their bearing on the generation and crystallization of basaltic magma, *Contrib. Mineral. Petrol.* 66 (1978) 203–220.
- 36 T.H. O'Donnell and D.C. Presnall, Chemical variations of the glass and mineral phases in basalts dredged from 25°–30°N along the Mid-Atlantic ridge, *Am. J. Sci.* 280-A (1980) 845–868.
- 37 G. Thompson, W.B. Bryan and W.G. Melson, Geological and geophysical investigation of the Mid-Cayman Rise spreading center: geochemical variation and petrogenesis of basalt glasses, *J. Geol.* 88 (1980) 41–55.
- 38 M.F.J. Flower, Thermal and kinematic control on ocean-ridge magma fractionation: contrasts between Atlantic and Pacific spreading axes, *J. Geol. Soc. London* 138 (1981) 695–712.
- 39 M.J. Flower, Accumulation of calcic plagioclase in ocean ridge tholeiite: an indication of spreading rate?, *Nature* 287 (1980) 530–532.
- 40 A.E. Bence, J.J. Papike and R.A. Ayuso, Petrology of submarine basalts from the Central Caribbean: DSDP Leg 15, *J. Geophys. Res.* 80 (1975) 4775–4804.
- 41 R.A. Ayuso, A.E. Bence and S.R. Taylor, Upper Jurassic tholeiitic basalts from DSDP Leg 11, *J. Geophys. Res.* 81 (1976) 4305–4325.
- 42 M.A. Dungan and J.M. Rhodes, Residual glasses and melt inclusions in basalts from DSDP Legs 45 and 46: evidence for magma mixing, *Contrib. Mineral. Petrol.* 67 (1978) 417–431.
- 43 M.A. Dungan, P.E. Long and J.M. Rhodes, Magma mixing at mid-ocean ridges: evidence from Leg 45 and 46—DSDP, *Geophys. Res. Lett.* 5 (1978) 423–425.
- 44 M.R. Fisk and A.E. Bence, Experimental crystallization of chrome spinel in FAMOUS basalt 527-1-1, *Earth Planet. Sci. Lett.* 48 (1980) 113–123.
- 45 J.M. Rhodes, M.A. Dungan, D.P. Blanchard and P.E. Long, Magma mixing at mid-ocean ridges: evidence from basalts drilled near 22°N on the Mid-Atlantic Ridge, *Tectonophysics* 55 (1979) 35–61.
- 46 J.G. Moore, Water content of basalt erupted on the ocean floor, *Contrib. Mineral. Petrol.* 28 (1970) 272–279.