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Anhydrous Partial Melting of Peridotite from 8 to 35 kb and the Petrogenesis of MORB

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ABSTRACT

Equilibrium partial melts under anhydrous conditions have been determined for a MORB pyrolite composition (considered suitable for the production of primary MORB melts) from 8 to 35 kb and a relatively more depleted peridotite composition, Tinaquillo lherzolite, at 15 and 20 kb. The equilibrium partial melts were determined using 'sandwich' experiments. The primitive MORB glass DSDP3-18-7-1 was used in experiments using MORB pyrolite while a calculated liquid composition from Jacques & Green (1980) was used in experiments with Tinaquillo lherzolite. The equilibrium partial melts in conjunction with previous studies are used to establish a melting grid from 5 to 35 kb in the CIPW normative basalt tetrahedron. Equilibrium partial melts from MORB pyrolite combined with constraints imposed by the composition of primitive MORB glasses, MORB picrites and primitive trapped glass inclusions are subjected to olivine fractionation calculations to establish the range in composition of primary MORB melts. The results suggest primary MORB melts segregate from MORB source diapirs at pressures of 8 to 25 kb in equilibrium with either lherzolite or harzburgite residues. MgO contents of primary MORB melts range from 10–17 wt.% while primary melts with > 17 wt.% MgO are of minor importance. Primary MORB melts range in composition from slightly ne-normative and more hy-normative picrites to olivine and quartz normative olivine tholeiite. Although some primitive MORB glass compositions are possible primary melts from 8–20 kb the majority of primitive MORB glass compositions are derived by olivine fractionation (11–25 wt.%) from more picritic parents from pressures of 15–25 kb. The results of this study are in agreement with previous workers suggesting that there is an array of primary MORB melt compositions which evolve to multiple saturation in olivine + plagioclase + clinopyroxene at different points along a 1 atm. cotectic via differing degrees of olivine fractionation.

INTRODUCTION

The nature, composition, and depth of origin of primary magmas parental to mid ocean ridge basalts (MORB) is at the present time a subject of controversy (Thompson, 1987; Basaltic Volcanism Study Project, 1981; Wilkinson, 1982; Fujii & Bougault, 1983; Elthon & Scarfe, 1984; Presnall & Hoover, 1984, 1986; Fujii & Scarfe, 1985; Elthon, 1986; Falloon & Green, 1987; Green *et al.*, 1987). A commonly held model is that the more primitive* MORB glasses recovered from the ocean floors are close to or are primary magmas, generated by partial melting of upper mantle peridotite at depths of approximately 30 km (10 kb). This is attributed to a cusp in the peridotite solidus at ~ 30 km. A second competing model states that the more primitive MORB glasses are not primary magmas but are fractionated compositions lying on olivine control lines from more picritic parents which are themselves primary magmas at pressures of 15–25 or 30 kb. The former model has been tested by numerous experimental studies via a two-pronged approach of high pressure near liquidus studies of primitive MORB glasses combined with direct partial melting studies of peridotite compositions. The results and interpretations of these experimental studies are the cause of

* as measured by higher values of *mg*-number, ($Mg/(Mg + Fe^{2+})$), calculated assuming $Fe^{2+}/(Fe^{2+} + Fe^{3+}) = 0.9$.

the controversy regarding the primary or non-primary nature of primitive MORB glasses. High-pressure near liquidus studies of primitive MORB glasses (Bender *et al.*, 1978; Green *et al.*, 1979; Fujii & Bougault, 1983) have not been successful in demonstrating multiple saturation in olivine + orthopyroxene \pm clinopyroxene near the liquids at any pressure, as expected for possible equilibrium with lherzolite or harzburgite residues (see Falloon & Green, 1987 for a more complete discussion). Green *et al.* (1979) considered the failure of the primitive MORB glass DSDP3-18-7-1 to crystallize orthopyroxene near the liquidus at any pressure, to be evidence for the non-primary nature of primitive MORB glasses. They demonstrated that a more olivine enriched parental composition (DSDP3-18-7-1 + 17wt.% olivine) is a possible primary magma at 20 kb in equilibrium with a harzburgite residue.

In the second approach of direct melting studies of peridotite compositions the majority of studies have demonstrated that liquid compositions produced from suitable source compositions are unlike primitive MORB glasses at 10 kb (Jaques & Green, 1980; Stolper, 1980; Sen, 1982; Takahashi & Kushiro, 1983; Elthon & Scarfe, 1984; Fujii & Scarfe, 1985; Falloon & Green, 1987; Takahashi, 1986). Specifically, Falloon & Green (1987) demonstrated that 10 kb partial melts from four peridotite compositions, Hawaiian and MORB pyrolite, Tinaquillo lherzolite and spinel lherzolite KLB-1, were unlike primitive (*mg*-number ≥ 0.68) MORB glasses. Falloon & Green (1987) also discuss previous melting studies highlighting the problems of Fe-loss to noble metal containers, quench modification of primary equilibrium glass compositions and the use of inappropriate bulk compositions as a cause of differences in interpretation over the nature of primary MORB magmas.

The results of the study by Falloon & Green (1987) leave a picrite primary magma as the only alternative. However a picrite primary magma is considered unacceptable by many workers for the following reasons:

- (1) If a picrite melt model requires extensive olivine fractionation to produce primitive MORB glasses, then based on Ni partitioning data (Sato, 1977; Hart & Davis, 1978), Ni should be depleted to much lower levels than observed in primitive MORB glasses.

- (2) Absence of primitive MORB glasses of picritic compositions.

- (3) Absence of abundant cumulate rocks of dunitic composition from dredge hauls of oceanic ridges and fracture zones. Most commonly, ultramafic rocks consist of lherzolite and gabbroic material.

- (4) The failure to date of any experimentally produced picrite composition to yield MORB like compositions when subjected to olivine fractionation calculations.

- (5) For many workers, the consistent observation of olivine tholeiites and quartz tholeiites over the sampled areas of the entire 66000 km ridge system is compelling evidence that these, and not the rare or absent picrite lavas, must be primary magmas.

In this paper we present the results of a partial melting study on a MORB pyrolite composition, suitable for the production of primary MORB magmas, from pressures of 8 to 35 kb, and from a slightly more depleted composition, Tinaquillo lherzolite, at pressures of 15 and 20 kb. The partial melts were determined using a peridotite-basalt 'sandwich' technique. In experiments using MORB pyrolite the primitive MORB glass DSDP3-18-7-1 (Table 1, no.4) was used as the basalt in the sandwich; in the case of Tinaquillo lherzolite a calculated liquid from Jaques & Green (1980) was used (Table 1, no.5).

The results of the melting study are used to determine the range in composition, and depth of origin of possible picritic primary magmas parental to primitive MORB glasses and eventually more typical MORB compositions. The results of this study demonstrate that highly MgO-rich (> 17 wt.%) picrites are only one end member of a spectrum of primary magmas which range to more basaltic primary magmas of 10–11 wt.% MgO.

EXPERIMENTAL APPROACH AND TECHNIQUE

The MORB pyrolite composition chosen for study is that calculated by Green *et al.* (1979). This composition is the result of combining a primary MORB picrite composition (DSDP3-18-7-1 + 17 wt.% olivine, mix E, Green *et al.*, 1979) with a harzburgite residue. The MORB picrite composition was experimentally demonstrated to be multiply saturated in olivine and orthopyroxene at 1430 °C, 20 kb, indicating possible equilibrium with a harzburgite residue (Green *et al.*, 1979). Two pyrolite compositions were used (Table 1, no.1 and 2 respectively) designated MPY-87 and MPY-90-40. MPY-90-40 is the MORB pyrolite composition of Green *et al.* (1979) minus 40 wt.% olivine (Fo_{91.6}) and MPY-87 is a result of recalculating the MORB pyrolite composition from a *mg*-number of 90 to 87 to produce a more Fe-rich pyrolite composition (cf. Wilkinson, 1982). The Tinaquillo lherzolite composition studied (TQ-40, Table 1, no.3) has also been modified by subtraction of 40 wt.% olivine. All three compositions were studied at 10kb by Falloon & Green (1987).

Olivine contains only Mg, Fe, and Ni in solid solution, thus extracting 40 wt.% olivine from the lherzolite and pyrolite compositions cannot affect phase relations or phase

TABLE 1
Starting compositions used in partial melting experiments

	1	2	3	4	5
SiO ₂	44.32	47.15	47.50	49.70	49.16
TiO ₂	0.16	0.28	0.13	0.72	0.52
Al ₂ O ₃	4.33	7.28	5.35	16.40	14.32
FeO	9.82	7.27	7.51	7.90	11.06
MnO	0.10	0.12	0.18	0.12	0.00
MgO	36.84	30.57	32.80	10.10	14.49
CaO	3.34	5.63	4.97	13.10	10.80
Na ₂ O	0.39	0.66	0.30	2.00	1.37
K ₂ O	0.00	0.00	0.03	—	—
P ₂ O ₅	0.00	0.00	0.02	—	—
Cr ₂ O ₃	0.44	0.75	0.75	0.07	—
NiO	0.25	0.29	0.43	0.03	0.00
Total	99.99	100.00	99.97	100.14	99.72
<i>mg</i> -no.	0.87	0.88	0.89	0.69	0.70
	<i>CIPW norm (molecular)</i>				
Ab	2.14	3.97	1.79	15.09	9.70
An	6.16	11.33	8.73	30.07	25.97
Di	3.98	7.39	7.54	24.56	16.29
Hy	13.20	22.22	27.97	12.10	13.66
Ol	72.52	52.56	51.69	14.69	31.26
CaO/Al ₂ O ₃	0.77	0.77	0.93	0.79	0.75
CaO/Na ₂ O	8.56	8.53	16.56	6.55	7.88
CaO/TiO ₂	20.87	20.11	38.23	18.19	20.77
Al ₂ O ₃ /TiO ₂	27.06	26.00	41.15	22.77	27.54

- (1) MORB pyrolite composition MPY-87
 - (2) MORB pyrolite composition MPY-90-40 (MPY-90 minus 40 wt.% olivine Mg_{91.6}Fe_{8.1}Ni_{0.2}Mn_{0.1})
 - (3) TQ-40 (Tinaquillo lherzolite minus 40 wt.% olivine Mg_{91.9}Fe_{8.0}Mn_{0.1})
 - (4) Primitive MORB glass DSDP3-18-7-1 (Green *et al.*, 1979)
 - (5) Jaques & Green (1980) calculated melt composition from Tinaquillo lherzolite, 15 kb 1350 °C. Composition given is the mix composition as determined by broad beam electron microprobe analysis
- mg*-number calculated on basis of total iron as FeO. CIPW norm calculated on basis of Fe²⁺/(Fe²⁺ + Fe³⁺) = 0.9
- (—) below detection limit:

compositions in any way except in Mg, Fe, or Ni concentration, as long as olivine is a residual phase. In other words, the effect of extracting 40 wt.% olivine of Fo_{91} composition will only be to lessen the buffering role of olivine *mg*-number and Ni content; thus liquids and residues for pyrolite–40 wt.% olivine will change in *mg*-number and Ni content with increasing degree of melting a little more rapidly than for pyrolite. The net result of olivine subtraction is to increase the modal abundance of pyroxene, spinel and melt at the expense of olivine, and to slightly underestimate the *mg*-number of liquids and residues in equilibrium with residual olivine of $<Fo_{91}$ (i.e. low degrees of melting) and to slightly overestimate the *mg*-number of liquids and residues in equilibrium with olivine of $>Fo_{91}$.

Both Tinaquillo lherzolite and MORB pyrolite compositions are suitable source compositions for generating primary MORB magmas by partial melting, based on a comparison with natural peridotite suites (Nickel & Green, 1984; Frey *et al.*, 1985; Falloon & Green, 1987). The aim of this study is to test the ability of these two compositions to produce primary picritic or basaltic MORB magmas, i.e. a detailed matching of observed equilibrium melts with natural MORB.

The basalt–peridotite ‘sandwich’ technique has been used successfully in a number of previous studies to determine equilibrium partial melt compositions (Stolper, 1980; Takahashi & Kushiro, 1983; Fujii & Scarfe, 1985; Falloon & Green, 1987). Potential problems associated with the ‘sandwich’ technique have been discussed and evaluated by Falloon & Green (1987). In the ‘sandwich’ technique a layer of basalt is placed in between layers of peridotite and allowed to equilibrate with the peridotite and its partial melt at a desired pressure and temperature. This provides a large area of glass to be analysed at the end of the run and avoids the problem of quench modification of primary liquids.

All the starting mixes (Table 1) were made up by sintering high purity oxides, crushed in acetone and fired at 1000 °C. Fayalite was then added to the mixes before refiring in a silica evacuated tube at 1000 °C. The mixes were stored in an oven at 110 °C. The mixes were loaded into graphite capsules and sealed in an outer platinum capsule. In some experiments an outer platinum capsule was not used; no differences were observed between liquid compositions run in unsealed or sealed capsules. Two sizes of graphite capsules were used; in the large bore graphite capsule, a layer of DSDP3-18-7-1 mix was loaded between layers of MORB pyrolite. In the small bore graphite capsules only two layers were used the basalt layer forming the top layer (DSDP3-18-7-1 or Jaques & Green, 1980 calculated liquid in the case of Tinaquillo lherzolite).

All experiments were carried out in a high pressure piston cylinder apparatus at the University of Tasmania, using a piston-in technique with a pressure correction of minus 10% nominal piston pressure. A 0.5 in. diameter, talc-pyrex assembly was used with a graphite heater. A pure alumina thermocouple sheath was used, with sintered alumina components surrounding the capsule. The thermocouple sheath enters the assembly through a mullite sleeve. The bottom spacer is fired pyrophyllite (mullite and silica).

Both Pt/Pt₉₀Rh₁₀ and W₇₅Re₂₅/W₉₇Re₃ thermocouples were used in the course of the experimental study. Thermocouple drift was experienced on long runs when using the Pt/Pt₉₀Rh₁₀ thermocouple (see also Falloon & Green, 1987). The W₇₅Re₂₅/W₉₇Re₃ thermocouples were controlled by a Kent P96M controller, temperatures being accurate to ± 1 °C.

At the end of the run the sample was removed from the graphite capsule and sectioned longitudinally for microprobe analysis. All analyses were done at the University of Tasmania on a JEOL JX 50A electron microprobe (EMP) scanning electron microscope, fitted with an energy dispersive EDAX analytical system (operating conditions 15kV, 7×10^{-10} A); calibration was on pure Cu. Back scattered electron photographs were taken of

TABLE 2
Experimental run details of 'sandwich' experiments on MORB pyroxene and Tinnakillo lherzolite compositions

Run no.	P (kb)	T (°C)	Time (h)	Capsule type	Capsule	Peridotite	Wt. % basalt	Phases present
T-1516	8	1350	24	B	Pt/C	MPY-87	4.7	Ol + Cpx + Opx + L
T-1512	8	1400	24	B	Pt/C	MPY-87	6.25	Ol + Opx + L
T-1479	12	1450	12	B	Pt/C	MPY-87	9.5	Ol + Opx + L
T-1994	12	1375	6.5	B	C	MPY-90-40	9.9	Ol + Opx + Cpx + L
T-2189	12	1400	21	A	Pt/C	MPY-90-40	20	Ol + Opx + L
T-1989	15	1360	6.5	B	C	MPY-90-40	11.1	Ol + Opx + Cpx + Sp + L
T-1999	15	1420	3	B	C	MPY-90-40	14.1	Ol + Opx + Cpx + L
T-2192	15	1450	20	A	Pt/C	MPY-90-40	24	Ol + Opx + L
T-2056	15	1450	24	A	Pt/C	TQ-40	23	Ol + Opx + L
T-2029	18	1370	26	A	C	MPY-90-40	6.25	Ol + Opx + Cpx + Sp + L
T-2031	18	1450	42.5	A	C	MPY-90-40	10.39	Ol + Opx + Cpx + Sp + L
T-2069	20	1500	24	A	Pt/C	TQ-40	26	Ol + Opx + L
T-1515	20	1420	24	B	Pt/C	MPY-87	5	Ol + Opx + Cpx + Sp + L
T-1501	20	1430	24	B	Pt/C	MPY-87	10	Ol + Opx + Cpx + Sp + L
T-1513	20	1450	1.2	B	Pt/C	MPY-87	10	Ol + Opx + Cpx + Sp + L
T-1499	20	1475	1.0	B	Pt/C	MPY-87	9.4	Ol + Opx + Cpx + Sp + L
T-2207	20	1500	16	A	Pt/C	MPY-87	12	Ol + Opx + L
T-2086	25	1550	24	A	Pt/C	MPY-90-40	21	Ol + Opx + Cpx + L
T-2065	30	1600	23	A	Pt/C	MPY-90-40	16	Ol + Opx + Cpx + L
T-2075	30	1920	6	A	Pt/C	MPY-90-40	23	Ol + Opx + L
T-2087	35	1600	24.5	A	Pt/C	MPY-90-40	9	Ol + Opx + Cpx + Ga + L

A and B refer to small and large bore graphite capsules respectively.
 Pt = platinum, C = graphite, Ol = olivine, Opx = orthopyroxene, Cpx = clinopyroxene, Sp = spinel, Ga = garnet, L = liquid (glass).

all run products to check on the compositional uniformity of all the phases (Phillips 505 SEM, operating conditions 20 kV, spot size 100 nm).

EXPERIMENTAL RESULTS

Details of the experimental runs are given in Table 2. The compositions of equilibrium partial melts produced in the experiments are given in Tables 3 and 4. The compositions of the partial melts are plotted in the CIPW molecular normative basalt tetrahedron in Fig. 2 and compared with primitive MORB glasses.

Attainment of equilibrium

In runs at 8, 12, 15 and 18 kb the basalt layer was quenched as a coherent glass layer (100–300 μm) between or on top of the peridotite layer(s) which consist of crystals and glass. In runs close to the solidus abundant clinopyroxene crystallization occurred within the glass layer, in these cases the glass composition was obtained by analysing large pools of glass (50–70 μm).

TABLE 3

Equilibrium partial melt compositions from MORB pyrolite (MPY-88) and Tinaquillo lherzolite

<i>P</i> (<i>kb</i>)	MPY-87							Tinaquillo		
	1 8	2 8	3 12	4 20	5 20	6 20	7 20	8 20	9 15	10 20
SiO ₂	51.09	52.63	49.64	47.03	46.94	47.52	47.39	48.75	48.97	47.52
TiO ₂	0.65	0.58	0.59	1.00	0.70	0.73	0.60	0.53	0.42	0.52
Al ₂ O ₃	16.26	14.50	14.34	16.62	15.44	14.39	14.26	11.97	13.77	12.96
FeO	7.32	7.39	8.58	9.67	9.83	9.62	9.44	9.71	6.87	8.29
MgO	10.25	11.68	13.83	12.99	14.24	14.51	15.46	17.67	15.52	17.17
CaO	12.16	11.14	11.10	9.93	10.53	10.98	10.94	9.56	12.98	12.09
Na ₂ O	1.91	1.66	1.65	2.63	2.30	1.84	1.60	1.36	1.07	1.03
K ₂ O	—	—	—	0.12	—	—	—	—	—	—
Cr ₂ O ₃	0.35	0.41	0.59	—	0.20	0.38	0.28	0.53	0.36	0.39
Total	99.99	99.99	100.32	99.99	100.18	99.97	99.97	100.08	99.96	99.97
<i>mg</i> -no.	0.73	0.76	0.76	0.73	0.74	0.75	0.76	0.80	0.82	0.81
<i>CIPW norm (molecular)</i>										
Qz	0.00	7.65	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ne	0.00	0.00	0.00	1.81	1.06	0.00	0.00	0.00	0.00	0.00
Ab	14.84	12.08	12.04	16.37	14.66	12.84	11.10	9.47	7.66	7.09
An	31.00	26.05	25.79	25.56	24.23	24.11	24.53	20.60	26.13	23.58
Di	21.24	18.78	18.19	12.37	15.56	18.24	17.43	16.18	25.21	22.43
Hy	26.63	32.04	21.45	0.00	0.00	6.97	8.86	22.20	16.85	11.74
Ol	2.55	0.00	18.29	39.23	40.90	33.88	34.66	28.66	21.40	31.99
CaO/Al ₂ O ₃	0.75	0.76	0.77	0.60	0.68	0.76	0.77	0.79	0.94	0.93
CaO/Na ₂ O	6.36	6.71	6.73	3.77	4.58	5.97	6.84	7.03	12.13	11.74
CaO/TiO ₂	18.71	19.21	18.81	9.93	15.04	15.04	18.23	18.04	30.90	23.25
Al ₂ O ₃ /TiO ₂	25.01	25.00	24.30	16.62	22.06	19.71	23.77	22.58	32.78	24.92
PM %	27.0	30.0	28.0	12.0	17.0	24.0	28.0	36.0	17.0	17.0
Residue	L	H	H	L	L	L	H	H	H	H
Temp (°C)	1350	1400	1450	1420	1430	1450	1475	1500	1450	1500

L = lherzolite residue, H = harzburgite residue.

mg-number and CIPW norm calculated on the basis of $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Fe}^{3+}) = 0.9$.

(—) below detection limit.

TABLE 4
Equilibrium partial melt compositions from MORB pyroxite (MPY-90-40)

P (kb)	1		2		3		4		5		6		7		8		9		10		11		
	12	12	12	12	15	15	15	15	15	15	18	18	18	18	25	25	30	30	30	30	35	35	
SiO ₂	49.86	50.09	50.50	49.11	49.19	47.78	47.88	46.86	46.72	46.99	45.83												
TiO ₂	0.69	0.59	0.82	0.69	0.59	1.52	0.66	0.66	0.55	0.50	1.08												
Al ₂ O ₃	17.18	15.00	18.00	15.88	14.58	17.31	15.16	13.73	12.71	12.21	11.70												
FeO	6.74	7.13	7.00	7.38	7.36	9.03	8.12	8.06	8.40	8.09	9.04												
MgO	11.13	13.04	10.00	12.97	14.42	10.89	14.58	17.75	19.31	20.23	19.99												
CaO	11.96	12.14	9.60	11.69	11.79	9.45	11.64	10.92	10.60	10.12	10.66												
Na ₂ O	2.06	1.63	3.50	1.87	1.67	3.66	1.56	1.60	1.19	1.31	1.36												
K ₂ O	—	—	—	—	—	0.14	—	—	—	—	—												
Cr ₂ O ₃	0.34	0.35	0.82	0.37	0.38	—	0.36	0.38	0.51	0.52	0.42												
Total	99.96	99.97	100.24	99.96	99.98	99.78	99.96	99.96	99.99	99.97	100.08												
mg-no.	0.77	0.78	0.74	0.78	0.80	0.70	0.79	0.81	0.82	0.84	0.82												
				CIPW norm (molecular)																			
Ne	0.00	0.00	0.0	0.00	0.00	5.86	0.00	0.00	0.00	0.00	0.00												
Ab	15.50	12.09	26.02	13.63	11.99	19.58	11.04	10.71	7.90	8.61	8.78												
An	31.55	27.78	27.67	28.38	25.82	23.54	27.11	22.57	21.71	20.09	18.57												
Di	18.19	21.99	11.78	18.73	20.95	12.77	18.44	17.81	17.20	16.67	19.46												
Hy	16.40	21.06	5.64	13.96	14.71	0.00	10.78	3.32	8.64	8.40	0.97												
Ol	14.70	13.71	25.40	21.63	23.19	32.17	29.05	42.20	41.23	43.12	48.25												
CaO/Al ₂ O ₃	0.69	0.81	0.53	0.74	0.81	0.54	0.77	0.79	0.83	0.83	0.91												
CaO/Na ₂ O	5.80	7.45	2.74	6.25	7.06	2.58	7.56	6.82	8.90	7.70	7.84												
CaO/TiO ₂	17.73	20.57	11.71	16.94	19.98	6.22	17.64	16.54	19.27	20.24	9.87												
Al ₂ O ₃ /TiO ₂	24.90	25.42	21.95	23.01	24.71	11.39	22.97	20.80	23.19	24.42	10.83												
PM %	23.0	30.0	5.0	25.0	28.0	10.0	22.0	27.0	33.0	37.0	15.0												
Residue	L	H	L	L	H	L	L	L	L	H	GL												
Temp (°C)	1375	1400	1360	1420	1450	1370	1450	1550	1600	1620	1600												

L = lherzolite residue, H = harzburgite residue, GL = garnet lherzolite residue.
 mg-number and CIPW norm calculated on the basis of $Fe^{2+}/(Fe^{2+} + Fe^{3+}) = 0.9$.
 (—) below detection limit.

In runs at higher pressure (20, 25, 30, and 35 kb) the basalt layer quenched to clinopyroxene and glass, the quench clinopyroxene becoming coarser with pressure. In these cases equilibrium partial melt compositions were determined by large broad beam area scans of the quench pyroxene and glass. In cases where the resulting broad beam area scan analyses were all uniform in composition, the liquid compositions were determined by averaging the area scans. In cases where a range in composition of the area scans was obtained, the area scans were observed to display good linear relationships when major oxides were plotted against *mg*-number (Fig. 1). This linear relationship is due to different proportions of quench modified glass and quench clinopyroxene of variable *mg*-number and composition ($0.74 < mg\text{-number} < 0.87$) in the area scans. The liquid compositions were determined by first calculating the equilibrium *mg*-number of the liquid in equilibrium with the olivine composition in the run based on the $(K_D)_{Fe/Mg}^{ol/liq}$ determined by Takahashi &

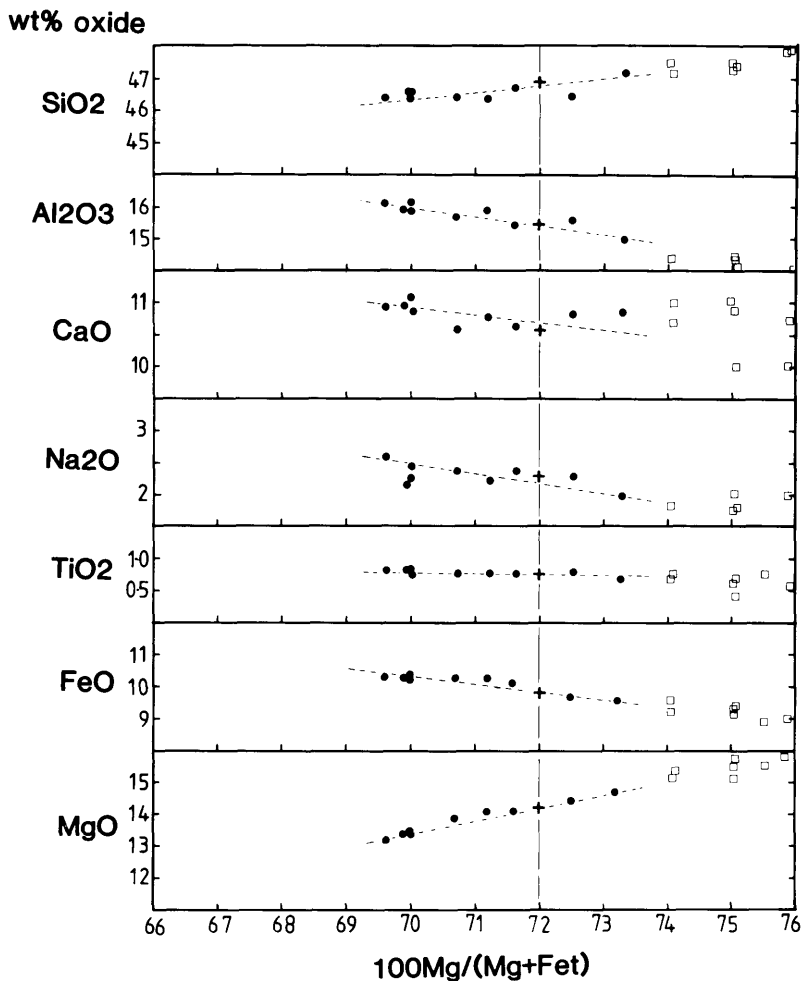


FIG. 1. Major element oxides SiO_2 , Al_2O_3 , CaO , Na_2O , TiO_2 , FeO and MgO vs $100\text{Mg}/(\text{Mg} + \text{Fe})$ for broad beam area scan analyses of the 'basalt' layer in run no. T-1501. (●) individual broad beam area scans. (+) calculated equilibrium partial melt composition. (□) spot analyses of quench clinopyroxene compositions. Thin line indicates the equilibrium $100\text{Mg}/(\text{Mg} + \text{Fe})$ ratio of a liquid composition in equilibrium with the olivine composition of the charge, based on the relationship of Takahashi & Kushiro (1983).

Kushiro (1983) for graphite capsules, and secondly reading off the major element composition of the liquid from the major oxide vs *mg*-number plots. An example is given for run T-1501 in Fig. 1. A few quench clinopyroxene analyses with *mg*-number of between 0.74 and 0.76 are shown in Fig. 1 to highlight the linear nature of the EMP broad beam area scans of the glass-quench clinopyroxene mixtures.

Due to the nature of the sandwich technique, modal homogeneity is not produced during the experiment, and although the melt phase is distributed throughout the charge, being in contact with all grain boundaries, the melt is concentrated in one layer. Due to the presence of this glass layer crystal growth is enhanced resulting in much larger and more abundant clinopyroxene and orthopyroxene crystals near the glass/peridotite (now crystals + glass) contact. All phases near or in the glass layer were found to be compositionally uniform from core to rim even for short run times. However phases away from the glass layer were not compositionally uniform from core to rim. Rim compositions were identical to the cores and rims of phases close to the glass layer, while cores were of a different composition. As a result of this zoning in crystals removed from the glass layer, bulk equilibrium was not achieved during the length of even the longest runs, however local equilibrium was achieved between the glass composition and residual crystals near the glass layer and rims of crystals away from the glass layer. Equilibrium is also confirmed by comparing the glass compositions in short runs to compositions in long runs; differences are all within analytical uncertainty (see also Falloon & Green, 1987).

EQUILIBRIUM GLASS COMPOSITIONS

MORB pyrolite

In the projection from Di (Fig. 2a) onto the base of the basalt tetrahedron, liquid compositions from MORB pyrolite define olivine + orthopyroxene + clinopyroxene + liquid and olivine + orthopyroxene + liquid cotectics from 8 to 35 kb, the cotectics moving systematically with pressure towards the olivine apex. The movement of the cotectics with pressure is a consequence of the contraction of the olivine phase volume as predicted by O'Hara (1965). As pressure increases, for a given degree of partial melting, SiO₂ contents fall and melts become more FeO and MgO rich. Al₂O₃ contents of equilibrium liquids, for a given degree of partial melting, decrease due to the increasing Al₂O₃ contents of residual pyroxenes with pressure. This results in CaO/Al₂O₃ ratios greater than the bulk CaO/Al₂O₃ ratio of MORB pyrolite. Residual clinopyroxene becomes less calcic with increasing temperature at higher pressure, due to the narrowing of the pyroxene solvus, such that the CaO contents of liquids at the point of elimination of clinopyroxene become less calcic with increasing pressure.

The systematic movement of olivine + orthopyroxene + clinopyroxene + liquid and olivine + orthopyroxene + liquid cotectics towards the olivine apex with pressure is less obvious in the projection from plagioclase (Ab + An) (Fig. 2b), as the cotectics tend to be projected one on top of each other as a consequence of the three-dimensional relationships within the basalt tetrahedron. As the cotectics all form a slight angle to the join Jd + CaTs-Qz of the basalt tetrahedron (Fig. 2a), when a projection from plagioclase (Ab + An) is taken, the cotectics plot one on top of the other. This emphasizes the importance of looking at least two different projections to establish the three-dimensional relationships between different compositions. In the projection from Di, primitive MORB glasses overly ~5 to ~16 kb cotectics, however in the projection from plagioclase (Ab + An) primitive MORB glasses plot above these cotectics. Although this indicates that primitive MORB glasses are not primary

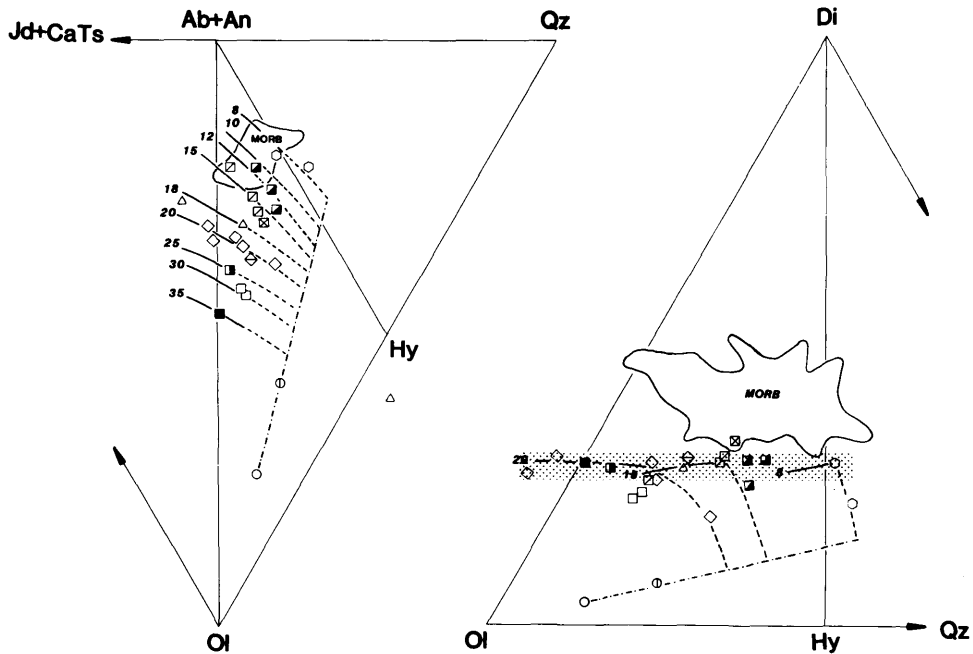


FIG. 2. (a) Equilibrium partial melt compositions from MORB pyrolite and Tinaquillo lherzolite plotted in the CIPW molecular normative basalt tetrahedron, projected from diopside (Di) onto the base jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz (Qz)-olivine (Ol). (○) MORB pyrolite (MPY-90-40). The following symbols represent partial melt compositions at the indicated pressures (kb). (○) 8, (◐) 12, (◑) 15, (◒) Tinaquillo 15, (△) 18, (◔) Tinaquillo 20, (◕) 20, (◖) 25, (◗) 30, (◘) 35. --- locus of liquids in equilibrium with olivine, - - - - - locus of liquids in equilibrium with olivine + orthopyroxene, ——— locus of liquids in equilibrium with olivine + orthopyroxene + clinopyroxene ± spinel. 10 kb cotectic from Falloon & Green (1987). MORB encloses field of primitive MORB glasses, references see caption to Fig. 6. (b) Equilibrium partial melt compositions from MORB pyrolite and Tinaquillo lherzolite plotted in the CIPW molecular normative basalt tetrahedron, projected from plagioclase (Ab + An) onto the face diopside (Di)-olivine (Ol)-quartz (Qz). Symbols and cotectic lines as for Fig. 2a. Shaded area encloses liquid compositions in equilibrium with olivine + orthopyroxene + clinopyroxene from MORB pyrolite (cf. Fig. 10). Algorithm for the projections are taken from Green (1970) as follows: co-ordinates for the basalt tetrahedron calculated from the following components of the CIPW molecular norm, Ab (albite), An (anorthite), Ne (nepheline), Hy (hypersthene, calculated on the basis of 6 oxygen formula unit), Ol (olivine), Qz (Quartz) and Di (diopside). For projection from Di:

Jd + CaTs = Ab + An + Ne,
 Qz = Ab + An + Hy + Qz - Ne,
 Ol = Ol + Hy,
 resummed to 100% for plotting.

For projection from plagioclase (Ab + An):
 Di = Di,
 Ol = Ol + Hy,
 Qz = Qz + Hy - 2Ne,
 resummed to 100% for plotting.

magmas, some of the glasses characterized by low normative Di in the projection from plagioclase (Ab + An) plot close to the cotectics indicating that possibly only small to moderate amounts of olivine fractionation is required to move equilibrium partial melt compositions into the field of primitive MORB glasses. This possibility will be discussed in another section of this paper.

Tinaquillo lherzolite

Equilibrium partial melts from sandwich experiments on Tinaquillo lherzolite at 15 and 20 kb are also plotted in Fig. 2. The 15 and 20 kb liquids are consistent with the 15 and 20 kb cotectics determined for MORB pyrolite. Although the 15 and 20 kb cotectics for Tinaquillo

lherzolite and MORB pyrolite overlie each other in Fig. 2(a), liquid compositions are distinctly different. The liquid compositions from Tinaquillo lherzolite compared to MORB pyrolite have higher CaO contents, lower Al_2O_3 , Na_2O and TiO_2 contents, and have higher $\text{CaO}/\text{Al}_2\text{O}_3$ and $\text{CaO}/\text{Na}_2\text{O}$ ratios.

COMPARISON WITH PREVIOUS EXPERIMENTAL STUDIES

In this section equilibrium partial melt compositions from MORB pyrolite are compared with liquid compositions produced in previous high pressure experimental studies of peridotite melting and other relevant experimental studies on MORB petrogenesis. For this comparison, the projection from Di in the basalt tetrahedron is used as the movement of olivine + orthopyroxene \pm clinopyroxene + liquid cotectics with pressure is well defined. The aim of this section is to emphasize the consistency in projected position of olivine + orthopyroxene \pm clinopyroxene + liquid cotectics and the movement of these cotectics with pressure despite differences in peridotite bulk compositions in the projection from Di. Although equilibrium partial melts reflect the respective bulk compositions, cotectics at a particular pressure will overly or plot close to one another in the basalt tetrahedron when projected from Di (Fig. 3) for a range of different peridotite bulk compositions. A detailed comparison of equilibrium partial melt compositions at 10kb is reported in Falloon & Green (1987).

Jaques & Green (1980)

Jaques & Green (1980) calculated equilibrium partial melts from Tinaquillo lherzolite and Hawaiian pyrolite at 2, 5, 10, and 15kb. Equilibrium partial melt compositions were determined by chemical analysis of all residual phases combined with complete modal analysis of the charge, taking into account the effect of Fe-loss. Liquid compositions were calculated by mass balance. Falloon *et al.* (1988) have extended the study of Jaques & Green (1980) to 20 and 30kb, using the approach of Jaques & Green (1980) combined with 'sandwich' reversal experiments using a calculated liquid composition as the basalt in the 'sandwich'. The results of the reversal experiments demonstrate that most calculated liquid compositions of Jaques & Green (1980) are too olivine normative, the equilibrium liquids being more silica saturated than calculated by Jaques & Green (1980) (Falloon *et al.*, 1988).

In Fig. 3 equilibrium cotectics from MORB pyrolite, Hawaiian pyrolite and Tinaquillo lherzolite are plotted. Despite three different peridotite compositions and correspondingly different equilibrium liquid compositions, liquid compositions can be used to define a single 'average' cotectic in the projection from Di (Fig. 3) for pressures from 5 to 30kb. In the projection from plagioclase (Ab + An), however, equilibrium liquids do not define a unique 'average' cotectic, as Hawaiian pyrolite liquids define a olivine + orthopyroxene + clinopyroxene + liquid cotectic at significantly higher normative Di contents than MORB pyrolite and Tinaquillo lherzolite. The results of this study and that of Falloon *et al.* (1988) and Falloon & Green (1987) provide an internally consistent data set for peridotite melting from 5 to 35kb. The cotectics from MORB pyrolite will be used as a point of reference when discussing the following experimental studies.

Takahashi & Kushiro (1983)

Takahashi & Kushiro (1983) determined equilibrium partial melts in equilibrium with olivine + orthopyroxene \pm clinopyroxene + liquid by the 'sandwich' technique using the

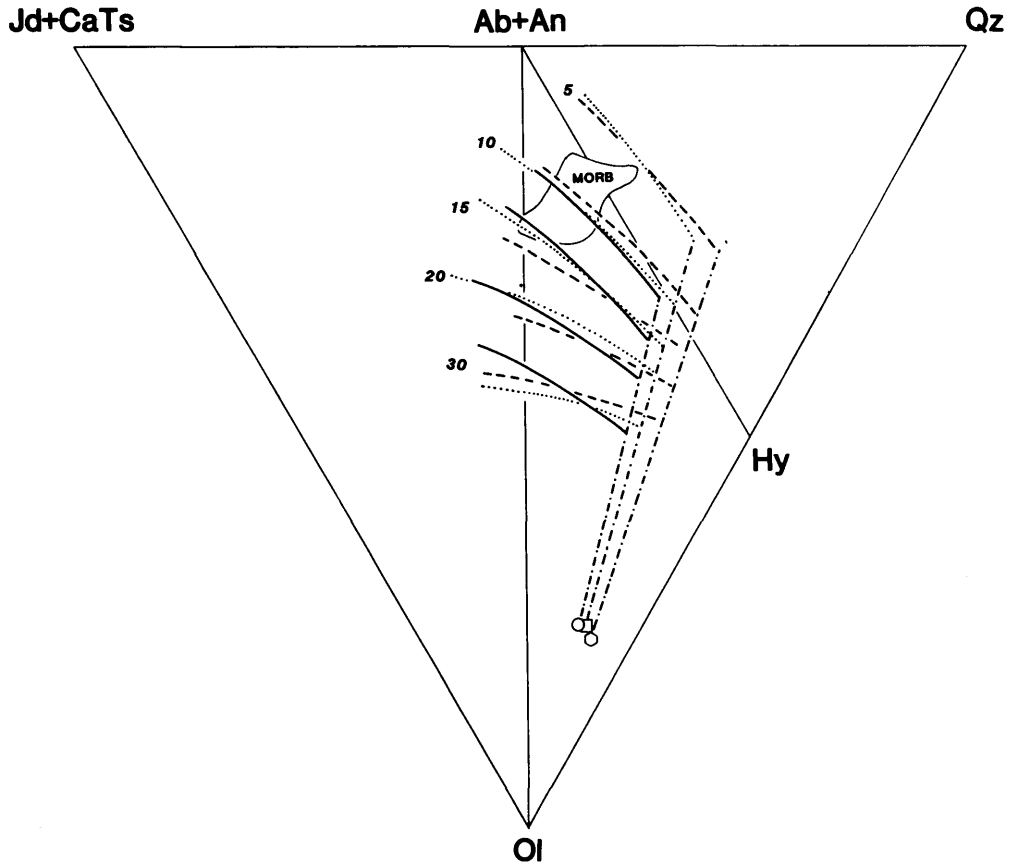


FIG. 3. Cotectics defined by partial melt compositions from MORB pyrolite (this study, and Falloon & Green, 1987), Hawaiian pyrolite and Tinaquillo lherzolite (Jaques & Green, 1980; Falloon *et al.*, 1988) at 5, 10, 15, 20, and 30 kb under anhydrous conditions as seen in the projection from diopside (Di) onto the base of the CIPW molecular normative basalt tetrahedron jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz (Qz)-olivine (OI). (○) MORB pyrolite, (□) Hawaiian pyrolite, (○) Tinaquillo lherzolite, - - - - - locus of liquids in equilibrium with olivine only, ——— locus of liquids in equilibrium with olivine + orthopyroxene ± clinopyroxene ± spinel for MORB pyrolite, locus of liquids in equilibrium with olivine + orthopyroxene ± clinopyroxene ± spinel for Hawaiian pyrolite, - - - - - locus of liquids in equilibrium with olivine + orthopyroxene ± clinopyroxene ± spinel for Tinaquillo lherzolite. MORB field as for Fig. 2.

fertile, Fe-rich spinel lherzolite HK66 and a diverse range of basalt compositions (MORB tholeiite, alkali basalt, boninite, picrite). Equilibrium liquid compositions from HK66 are plotted in Fig. 4. Equilibrium liquids define olivine + orthopyroxene + clinopyroxene + liquid and olivine + orthopyroxene + liquid cotectics at 5, 8, 10, 15, 20, 25, 30, and 35 kb. There is a problem with 25 kb liquid compositions from HK66 which plot with the 20 kb liquids in the projection from Di. There is also a problem with one of the 30 kb liquid compositions from HK66 which plots on top of the 35 kb cotectic from HK66 in the projection from Di (Fig. 4). The cotectics from HK66 overlie liquid compositions for MORB pyrolite, Hawaiian pyrolite and Tinaquillo lherzolite at 5, 15, 20, 30, and 35 kb. This result strongly suggests these cotectics at these pressures are correctly located in the projection from Di. The only inconsistencies are the 8 and 10 kb cotectics from HK66 which, particularly at the lower temperature ends, overlie 10 and 12 kb cotectics respectively from the other three peridotite

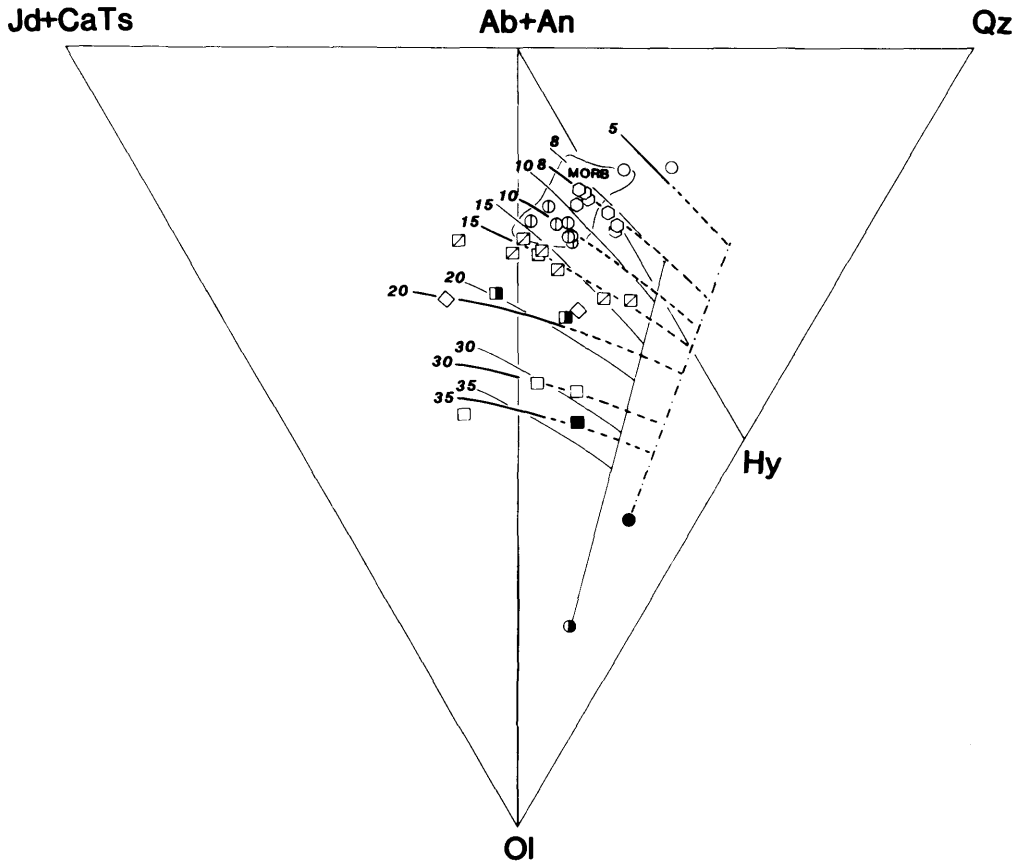


FIG. 4. Equilibrium partial melt compositions from spinel lherzolite HK66 (Takahashi & Kushiro, 1983) compared to cotectics defined by partial melt compositions from MORB pyrolite at 8, 10, 15, 20, 30, and 35 kb in the projection from Di onto the base of the CIPW molecular normative basalt tetrahedron jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz(Qz)-olivine (Ol). The following symbols represent partial melt compositions at different pressures (kb) from HK66. (○) 5, (○) 8, (○) 10, (◻) 15, (◇) 20, (◼) 25, (◻) 30, (◼) 35, (●) MORB pyrolite, (●) spinel lherzolite HK66, ——— cotectics (olivine + liquid, olivine + orthopyroxene + liquid, olivine + orthopyroxene + clinopyroxene ± spinel + liquid) from MORB pyrolite, - - - - - locus of liquids in equilibrium with olivine, - - - - - locus of liquids in equilibrium with olivine + orthopyroxene, ——— locus of liquids in equilibrium with olivine + orthopyroxene + clinopyroxene ± spinel. MORB field as for Fig. 2.

compositions. In view of the internal consistency of liquid compositions between MORB, Hawaiian pyrolite, and Tinaquillo lherzolite and the liquid cotectics at 5, 15, 20, 30, and 35 kb from HK66, the regular spacing and movement of cotectics with pressure towards the Ol-Jd + CaTs join in the Di projection, all suggest that the 8 and 10 kb cotectics from HK66 are possibly incorrectly located in the Di projection. This could be due to a possible small difference in pressure calibration with the piston-cylinder apparatus.

Takahashi (1986)

Takahashi (1986) published partial melt compositions from spinel lherzolite KLB-1 from 10 to 140 kb. Most liquid compositions reported by Takahashi (1986) are in equilibrium with olivine only, except for liquids at 10 and 30 kb. The 30 kb liquid from KLB-1 published by Takahashi (1986) and the 10 kb liquid from KLB-1 determined by Falloon & Green (1987)

overly and are therefore consistent with similar cotectics from MORB pyrolite, Hawaiian pyrolite, Tinaquillo lherzolite and spinel lherzolite HK66 (at 30 kb only) (Fig. 5).

Stolper (1980)

Stolper (1980) determined liquid compositions in equilibrium with olivine + orthopyroxene at 10, 15, and 20 kb by equilibrating a MORB glass composition with harzburgite in a 'sandwich' type experiment. The 15 and 20 kb liquids are compared with cotectics from MORB pyrolite in Fig. 5; 10 kb liquids from Stolper (1980) are discussed in Falloon & Green (1987). The 15 kb liquids from Stolper (1980) plot closer to the 18 kb cotectic from MORB pyrolite rather than the 15 kb cotectic. Similarly the 20 kb liquid plots closer to the 25 kb

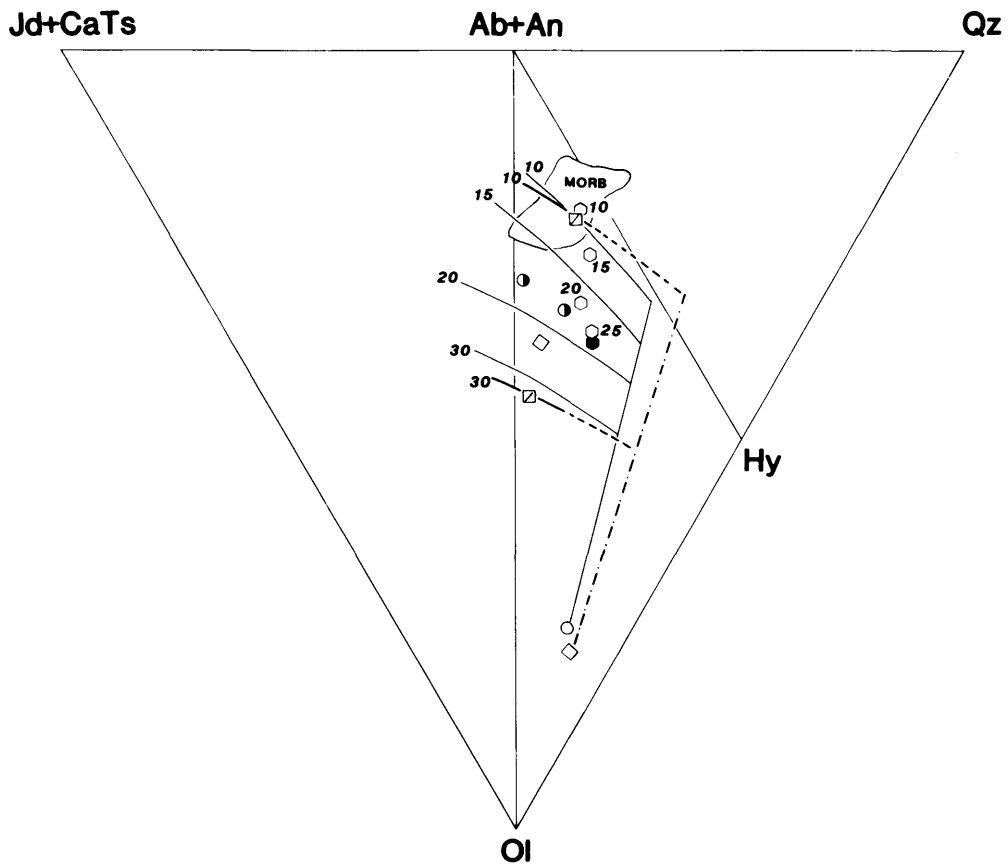


FIG. 5. Cotectics defined by partial melt compositions from MORB pyrolite (this study and Falloon & Green, 1987) at 10, 15, 20, and 30 kb compared to cotectics defined by spinel lherzolite KLB-1 at 10 and 30 kb (Takahashi, 1986; Falloon & Green, 1987) as well as liquid compositions from Stolper (1980) and Elthon & Scarfe (1984) in the projection from diopside (Di) onto the base of the CIPW molecular normative basalt tetrahedron jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz (Qz)-olivine (OI). (○) MORB pyrolite, (◇) spinel lherzolite KLB-1, (◻) partial melt compositions from KLB-1 Takahashi, 1986; Falloon & Green, 1987), (●, ◐) melt compositions in equilibrium with olivine + orthopyroxene at 15 and 20 kb respectively from Stolper (1980), (◆) bulk composition of NT-23 (Elthon & Scarfe, 1984), (◌) are the pseudoinvariant points at 10, 15, 20, and 25 kb from Elthon & Scarfe (1984). Cotectics as for Fig. 4. MORB field as for Fig. 2.

cotectic of MORB pyrolite. These differences are unlikely to be due to differences in bulk composition but may be due to systematic differences in pressure calibration using the piston-cylinder apparatus between the two different laboratories.

Elthon & Scarfe (1984)

Elthon & Scarfe (1984) studied the high pressure liquidus phase relations of a high-MgO picrite dyke composition NT-23 and determined the composition of liquids in equilibrium with olivine + orthopyroxene + clinopyroxene + garnet + liquid at 25 kb, olivine + orthopyroxene + clinopyroxene + liquid at 20 and 15 kb, and olivine + orthopyroxene + clinopyroxene + plagioclase + spinel + liquid at 10 kb. These liquid compositions are plotted in Fig. 5. The liquid compositions except for the 10 kb liquid are not consistent with any of the cotectics from MORB pyrolite. The 15, 20, and 25 kb liquid compositions from Elthon & Scarfe (1984) plot close to a 12, 15–17, and 18–20 kb cotectic respectively from MORB pyrolite. The bulk composition of NT-23 plots close to a 20 kb olivine + orthopyroxene + liquid cotectic from MORB pyrolite in Fig. 5 suggesting that NT-23 is a possible primary magma in equilibrium with a harzburgite residue. However Elthon & Scarfe (1984) report that NT-23 is multiply saturated at 25 kb with olivine + orthopyroxene + clinopyroxene + garnet, a result which is inconsistent with the compositions derived by partial melting of MORB pyrolite. A liquid in equilibrium with garnet at 20 or 25 kb is expected to lie in the Ne-normative side of the basalt tetrahedron. This conflict is attributed to misidentification of primary phases by Elthon & Scarfe (1984) in run no.164 (Elthon & Scarfe, 1984). In run no.164, primary olivine and orthopyroxene were large enough to be easily analysed (Elthon & Scarfe, 1984). However 'primary' clinopyroxene and garnet was apparently so small that glass-overlap was a potential problem. The low *mg*-number of the clinopyroxene (0.85) and garnet (0.76) compared with the primary olivine and orthopyroxene (0.90 and 0.89 respectively) suggests the clinopyroxene and garnet are quench phases. All phases should be large enough to analyse in a charge if primary. The result of run no.164 suggests multiple saturation in olivine and orthopyroxene only, consistent with results from MORB pyrolite, however the reported pressure of 25 kb is too high, 20 kb being more consistent.

Summary

The results of partial melting experiments on MORB pyrolite, Tinaquillo lherzolite, Hawaiian pyrolite (Jaques & Green, 1980; Falloon & Green, 1987; Falloon *et al.*, 1988), spinel lherzolite HK66 (Takahashi & Kushiro, 1983) and spinel lherzolite KLB-1 (Takahashi, 1986; Falloon & Green, 1987) provide an internally consistent set of data enabling the establishment of a melting grid in the projection from Di. This melting grid can be used to establish for any primitive magma composition a possible depth of magma segregation when projected from Di in the basalt tetrahedron. The melting grid also provides information on the possible residual phases and likely degree of partial melting of a primitive magma composition. In the following section the melting grid established for MORB pyrolite from 8 to 35 kb is used in conjunction with olivine fractionation calculations to establish a possible range of primary liquids parental to primitive MORB glasses, as well as the depth of magma segregation, degree of partial melting and how much olivine fractionation has occurred.

OLIVINE FRACTIONATION CALCULATIONS

Rationale

The rationale for these calculations is to test whether a simple model of equilibrium batch partial melting of a MORB pyrolite source, primary magma segregation, followed by olivine crystal fractionation can produce the range in composition of primitive MORB glasses, and to determine the range in pressures, temperatures, and degree of partial melting that is required. The assumption that olivine fractionation only has occurred since primary magma segregation, is supported by experimental studies of primitive MORB glasses, which have only olivine on their liquidus at 1 atm. (Bender *et al.*, 1978; Green *et al.*, 1979; Fujii & Bougault, 1983). Other workers have suggested that high pressure crystal fractionation of clinopyroxene ± orthopyroxene is also an important process (Bence *et al.*, 1979; Stolper, 1980; Elthon *et al.*, 1982; Fujii & Bougault, 1983; Elthon & Scarfe, 1984; Elthon, 1986). Evidence for this high pressure crystal fractionation include: (1) diopsidic clinopyroxene megacrysts rich in Cr (> 1 wt.%, Cr₂O₃) (Donaldson & Brown, 1977; Thompson 1980; Stakes *et al.*, 1984). (2) The 'clinopyroxene paradox' (Francis, 1986), where successful crystal-fractionation models require crystallizing assemblages dominated by clinopyroxene to explain the observed variation in major element geochemistry despite the absence or rarity of clinopyroxene as a phenocryst phase. The 'paradox' is explained by high-pressure clinopyroxene fractionation, with subsequent dissolution of high-pressure clinopyroxene at low pressure (O'Donnell & Presnall, 1980; Fujii & Bougault, 1983). (3) Cumulate rocks exposed in ophiolite sections, which include magnesian clinopyroxenes and orthopyroxenes (Elthon *et al.*, 1982; Elthon & Casey, 1985).

Concerning the first two points, experimental work by Grove & Bryan (1983) can reproduce the range in clinopyroxene composition observed in MORB at 1 atm. The presence of more magnesian (*mg*-number 0.90) clinopyroxene as well as calcic plagioclase megacrysts in MORB can be explained by contributions from refractory second-stage melts (Duncan & Green, 1980, 1987) in magma mixing processes in sub-axial magma chambers. They are not the result of high pressure crystal fractionation processes. Bryan *et al.* (1981) and Francis (1986) have suggested that the 'clinopyroxene paradox' is the result of an array of picritic parental compositions, fractionating olivine and arriving at different points along the 1 atm. olivine + plagioclase + clinopyroxene + liquid cotectic between the limiting cases of equilibrium and fractional crystallization. Francis (1986) proposes that the existence of the 'clinopyroxene paradox' in MORB glasses is evidence of the picritic nature of parental magmas for MORB, emphasizing the importance of olivine fractionation from picritic parents.

Concerning the third point, it is now doubtful whether most ophiolites represent major ocean basin crust, but rather dismembered pieces of island arc, forearc, and back-arc crust (Leitch, 1984). Thus inferences about processes at major mid ocean ridges from ophiolite cumulate sequences could be misleading. For example submarine lavas from the North Tonga forearc contain abundant magnesian orthopyroxene and clinopyroxene phenocrysts (Falloon *et al.*, 1987); lavas from the island of Mere Lava, Vanuatu arc, contain abundant magnesian clinopyroxenes (Barsdell, 1988). Both areas, if incorporated into an ophiolite terrain would show the presence of magnesian clinopyroxene or orthopyroxene in cumulate sequences. Cumulate sequences from a major mid-ocean ridge basin would be expected to be dominated by olivine + plagioclase + clinopyroxene, as is the case for the Macquarie Island ophiolite (Griffin & Varne, 1980).

Before presenting the results of olivine fractionation calculations there are several constraints which can be imposed on potential primary magma compositions. These

constraints are the major element composition of MORB glasses, and constraints derived from olivine control lines in the CIPW molecular normative basalt tetrahedron. Olivine control lines within the basalt tetrahedron form two important constraints on potential primary magma compositions:

(1) a potential peridotite source composition can only produce equilibrium partial melts to the left of an olivine control line passing through the bulk composition in the projection from Di (Green *et al.*, 1987) and above the olivine control line in the projection from plagioclase (An + Ab) in Fig. 2(b).

(2) potential primary/parental magmas to primitive MORB glasses must lie within olivine control lines bounding the range in silica saturation of primitive MORB glasses.

An important criterion for a MORB composition to be considered a primary magma is a *mg*-number (calculated with $\text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Fe}^{3+})$ equal to 0.9) appropriate to equilibrium with a mantle olivine composition of $\text{Fo}_{90 \pm 3}$ (Green, 1971). Using this criterion a data base of over 80 MORB glasses with *mg*-number ≥ 0.68 was obtained from the literature. Glass compositions were chosen as they represent liquid compositions and do not suffer from the effects of crystal accumulation and alteration (Melson *et al.*, 1977). The primitive MORB glasses display a significant range in major element and CIPW normative geochemistry, which is summarized in Table 5. This range in composition is a complex function of depth of magma segregation, source composition, degree of partial melting and extent of olivine fractionation. In conjunction with peridotite melting studies several important constraints based on the primitive MORB glass compositions have been selected; they are discussed separately below.

Constraints from the composition of primitive MORB glasses

Silica saturation

In terms of molecular normative mineralogy (Fig. 6) primitive MORB glasses range from ne-normative to quartz normative compositions. The primitive MORB glasses also display a significant range in normative diopside in the projection from plagioclase (Ab + An). Differing degrees of silica-saturation can be explained by differing degrees of partial melting, primary magmas produced by high degrees of partial melting will upon olivine fractionation move derivative compositions towards the qz-normative side of the diagram in Fig. 6. Primary magmas produced by low degrees of partial melting will on olivine fractionation move derivative liquids towards the ne-normative side of the diagram. At 10 kb equilibrium liquid compositions from MORB pyrolite (Falloon & Green, 1987) could not explain the range of silica saturation of primitive MORB glasses. At low degrees of partial melting the presence of the plagioclase phase volume acts as a barrier to low melting fraction liquids crossing over towards the ne-normative side of the diagram, while the elimination of clinopyroxene as a residual phase acted as a barrier to liquids crossing over to the quartz normative side of the diagram (Falloon & Green, 1987). Qz-normative glasses must either be low-pressure primary melts (< 10 kb) or derived by olivine fractionation from picritic liquids at higher pressures than 10 kb. In this case the picritic parents would be produced by relatively high degrees of partial melting, sufficient to eliminate clinopyroxene from the residue. Ne-normative glasses must be derived from parental magmas which are primary melts greater than 10 kb, the primary melts having an alkali picritic character, produced by smaller degrees of partial melting than parental magmas to hy-normative or qz-normative glasses. The degree of silica-saturation in the primitive MORB glasses is therefore broadly related to the degree of partial melting, ne-normative and low hy-normative glasses are

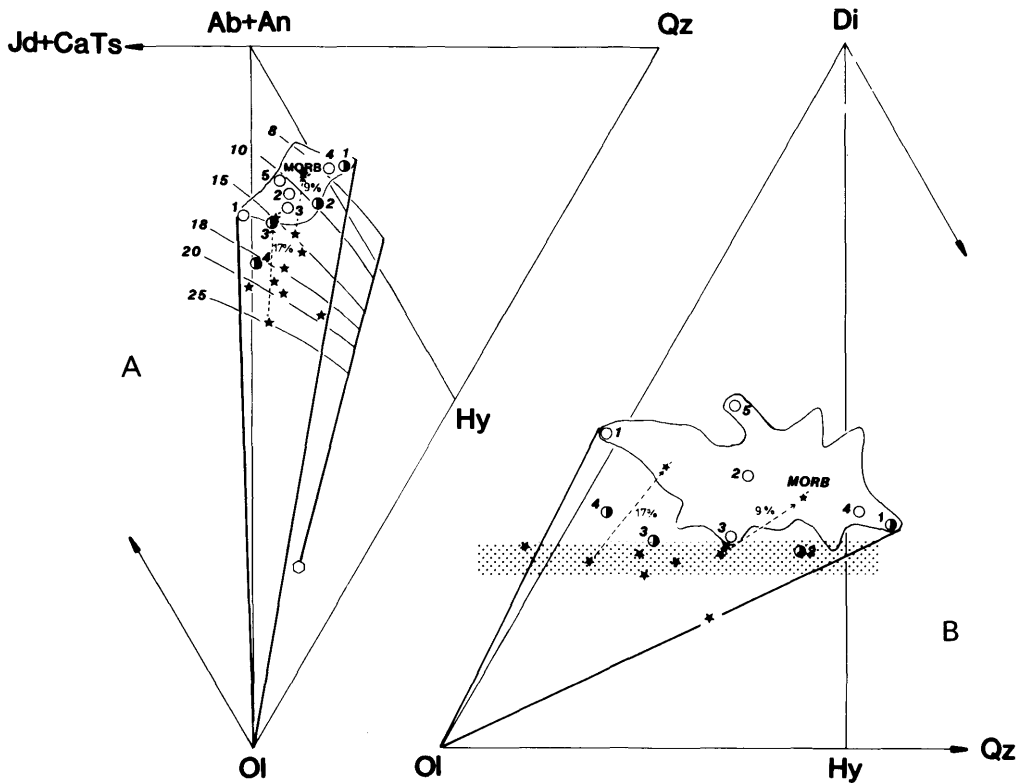


FIG. 6. Results of olivine fractionation calculations plotted in the CIPW molecular normative basalt tetrahedron projected from Di onto the base jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz (Qz)-olivine (Ol) in A, and onto the face diopside (Di)-quartz (Qz)-olivine (Ol) from plagioclase (Ab + An) in B. (★) equilibrium partial melts from MORB pyrolite which produced successful matches with primitive MORB glasses upon olivine fractionation. Examples of some successful fractionation paths (-----→) and wt.% olivine removed are also presented, (★') derivative liquid composition. (○) numbered 1 to 5 are primitive MORB glass compositions from Table 5, (●) numbered 1 to 4 are primary MORB compositions from Table 6, (○) MORB pyrolite, ———— olivine control lines, - - - - - cotectics from MORB pyrolite at 8, 10, 15, 18, 20 and 25 kb. Shaded area as for Fig. 2. MORB encloses field for primitive MORB glasses (Frey *et al.*, 1973, 1974; Melson, 1973; Hekinian *et al.*, 1976; Melson *et al.*, 1976, 1977; Byran & Moore, 1977; Langmuir *et al.*, 1977; Scarfe & Smith, 1977; Shipboard, S. P., 1977; Bender *et al.*, 1978; Bryan, 1979; Green *et al.*, 1979; Melson & O'Hearn, 1979; Shibata *et al.*, 1979; O'Donnell & Presnall, 1980; Basaltic Volcanism Study Project, 1981; Bryan *et al.*, 1981; Sigurdsson, 1981; Barker *et al.*, 1983; Fujii & Bougault, 1983; Natland *et al.*, 1984; Stakes *et al.*, 1984).

derived by lower degrees of partial melting than qz-normative and low ol-normative glasses which are derived by higher degrees of partial melting.

The range in normative Di contents displayed in Fig. 6 could be explained simply by differing degrees of olivine fractionation, glasses with higher normative Di in Fig. 6 having undergone more olivine fractionation than low olivine normative glasses. However in detail there is no simple relationship between low and high normative diopside glasses. This is probably a consequence of the superposition of olivine fractionation paths from multiple primary liquids in Fig. 6. Olivine fractionation paths from a range of primary melts at different pressures and degrees of partial melting are superimposed in this diagram. However in general high Di-normative glasses such as DSDP3-18-7-1 (Table 1) have undergone higher degrees of olivine fractionation than low Di-normative glasses.

Al₂O₃ and CaO contents

Important characteristics of primitive MORB glasses are their combined high CaO and Al₂O₃ contents (11.23–13.57 and 15.5–17.62 wt.% respectively, Table 5) compared with evolved MORB and primitive basalts of other tectonic regimes (e.g., evolved MORB from the Galapagos spreading center and East Pacific Rise) where CaO and Al₂O₃ contents range from 11.5 to 9 and 12 to 15 wt.% respectively for *mg*-number < 0.60 (Puchelt & Emmermann, 1983). Examples of primitive island arc basalts have recently been dredged from the north Tonga arc (Falloon & Green, 1986; Falloon *et al.*, 1987, 1988). These lavas have CaO and Al₂O₃ contents of 8.8–9.7 and 10.1–10.9 wt.% respectively at *mg*-number of 0.75–0.78. Primitive Hawaiian tholeiites (*mg*-number 0.66–0.71) have CaO and Al₂O₃ contents of 9.5–9.8 and 11.4–13.5 wt.% respectively (Basaltic Volcanism Study Project, 1981). Partial melting of peridotite at low pressures is unable to produce both high CaO and Al₂O₃ contents (Falloon & Green, 1987). At 10kbar low degrees of partial melting liquid compositions are characterized by high Al₂O₃ (>19 wt.%) and low CaO(<9 wt.%)

TABLE 5
Primitive MORB glass compositions

	1	2	3	4	5	min-max
SiO ₂	48.20	49.70	49.07	51.36	49.56	48.20–51.64
TiO ₂	0.51	0.72	0.74	0.78	0.67	0.50– 1.30
Al ₂ O ₃	17.00	16.40	16.44	15.03	15.90	15.50–17.62
FeO	8.51	7.90	8.86	7.86	8.29	7.30– 9.40
MnO	0.16	0.12	0.16	0.10	0.17	0.09– 0.25
MgO	10.10	10.10	10.15	9.01	9.19	8.10–10.70
CaO	12.70	13.10	11.65	12.38	13.57	11.23–13.57
Na ₂ O	2.34	2.00	2.13	2.04	2.15	2.40– 2.38
K ₂ O	0.04	0.01	0.07	0.10	0.07	0.01– 0.32
P ₂ O ₅	—	—	—	—	—	0.03– 0.14
Cr ₂ O ₃	—	0.07	0.03	0.11	—	0.01– 0.13
Total	99.56	100.12	99.30	98.77	99.57	
<i>mg</i> -no.	0.70	0.72	0.69	0.69	0.69	0.68– 0.73
<i>CIPW norm (molecular)</i>						
Qz	0.00	0.00	0.00	2.24	0.00	< 8.39
Ne	0.51	0.00	0.00	0.00	0.00	< 1.00
Ab	16.66	15.04	16.08	15.90	16.27	10.53–20.79
An	29.24	29.95	29.51	27.41	28.27	24.92–34.04
Di	22.27	24.50	19.09	25.92	28.49	18.76–29.45
Hy	0.00	11.63	13.24	24.16	6.79	<24.96
Ol	28.33	15.34	18.08	0.00	16.53	<28.33
CaO/Al ₂ O ₃	0.74	0.79	0.71	0.82	0.85	0.67– 0.88
CaO/Na ₂ O	5.42	6.55	5.47	6.07	6.31	4.58– 9.49
CaO/TiO ₂	24.90	18.19	15.74	15.87	20.25	9.32–25.60
Al ₂ O ₃ /TiO ₂	33.33	22.77	22.22	19.27	23.73	12.00–33.80

(1) ARP74-14-31 (Bryan, 1979).

(2) DSDP3-18-7-1 (Green *et al.*, 1979).

(3) ALV519-4-1 (Bryan & Moore, 1977).

(4) ALV526-1-1B (Bryan & Moore, 1977).

(5) 332B 36-3 (Shipboard S. P., 1977).

mg-number and CIPW norm calculated on the basis of Fe²⁺/(Fe²⁺ + Fe³⁺) = 0.9.

Min and Max indicate the range in composition of primitive MORB glasses (*mg*-number ≥ 0.68), data sources see caption to Fig. 6.

(—) not determined

contents and vice versa at higher degrees of partial melting (>25% partial melting, $\text{Al}_2\text{O}_3 < 15$ wt.%, $\text{CaO} < 12$ wt.%) (Falloon & Green, 1987). The Al_2O_3 and CaO contents in equilibrium with olivine + orthopyroxene \pm clinopyroxene residues, at a given degree of partial melting, will decrease as a function of increasing pressure, due to the increasing MgO and FeO content of the melt caused by the contraction of the olivine phase volume. Olivine fractionation increases both CaO and Al_2O_3 in derivative liquids from picritic parents so that the Al_2O_3 and CaO contents of primitive MORB glasses reflects the amount of olivine fractionation from the picritic parent.

SiO₂ contents

The SiO_2 contents of primitive MORB glasses range between 48.20 and 51.64 wt.%. As SiO_2 content along an olivine + orthopyroxene + clinopyroxene + liquid cotectic is primarily a function of pressure, and assuming the SiO_2 content of primitive MORB glasses is a primary feature, then a pressure range of between 20 to 8 kb is required to explain the SiO_2 content of primitive MORB glasses. However in reality the SiO_2 content of primitive MORB glasses is a function of both depth of primary melt segregation, degree of partial melting, and olivine fractionation.

FeO and MgO contents

FeO and MgO contents of primitive MORB glasses are a complex function of depth of primary magma segregation, bulk composition and degree of partial melting. Based on the results of this experimental study, for a given peridotite composition, FeO contents in partial melts will increase with pressure. At low pressures FeO contents of initial partial melts will be low relative to the FeO content of the bulk composition and FeO contents will increase with degree of partial melting (e.g., partial melts from MPY-87 at 8 kb have FeO contents of 7.32–7.39 wt.% compared to a bulk FeO content of 9.82 wt.%). At high pressures FeO contents of low melt fraction liquids will be higher or equal to the FeO content of the bulk composition, thus FeO contents will remain relatively constant or decrease with increasing partial melting (e.g., at 20 kb, partial melts from MPY-87 have 9.4–9.8 wt.% FeO and at 35 kb the partial melt composition from run T-2087 has an FeO content of 9.04 wt.% compared with a bulk FeO content of 7.27 wt.%, MPY-90-40 composition). The FeO contents of primitive MORB glasses vary from 7.3 to 9.4 wt.% and assuming that the glasses are primary melts then the FeO contents indicate depths of magma segregation of 15–20 kb based on a bulk composition with 7.5 wt.% FeO . The calculation of the CIPW normative molecular norm 'masks' FeO and MgO variation, causing compositions of differing FeO and MgO contents to plot in the same position within the basalt tetrahedron. Because FeO contents are sensitive to the bulk composition, the Fe/Mg ratio of equilibrium partial melts from MORB pyrolite can be varied to match the FeO contents of primitive MORB glasses.

CaO/Al₂O₃ and CaO/Na₂O ratios

Partial melting studies (Jaques & Green, 1980; Takahashi & Kushiro, 1983; Fujii & Scarfe, 1985), including this present work, demonstrate that $\text{CaO/Al}_2\text{O}_3$ and $\text{CaO/Na}_2\text{O}$ ratios vary systematically with degree of partial melting along a olivine + orthopyroxene + clinopyroxene + liquid cotectic. $\text{CaO/Al}_2\text{O}_3$ and $\text{CaO/Na}_2\text{O}$ ratios both increase with increasing degree of partial melting until clinopyroxene is eliminated from the residue, remaining relatively constant thereafter. The ratios of primitive MORB glasses could therefore be used as a constraint on the degree of partial melting. The stability of spinel during variable partial melting is a function of temperature and oxygen fugacity. In this experimental study spinel was eliminated as a distinct phase along with clinopyroxene due

to the low f_{O_2} present in the graphite capsules. However other experimental studies demonstrate (Jaques & Green, 1980; Fujii & Scarfe, 1985) that spinel can be stable as a residual phase to high degrees of partial melting, the spinel changing composition from an aluminous to a chrome-rich type with increasing degree of partial melting.

TiO₂, K₂O, and Al₂O₃/TiO₂ and CaO/TiO₂ ratios

Because K₂O and TiO₂ can be regarded as relatively incompatible during partial melting they can also be used as an indicator of the degree of partial melting. Ratios such as Al₂O₃/TiO₂ and CaO/TiO₂ vary systematically with partial melting along an olivine + orthopyroxene + clinopyroxene + liquid cotectic (Sun & Nesbitt, 1978; Sun *et al.*, 1979). However, because TiO₂, K₂O contents, Al₂O₃/TiO₂ and CaO/TiO₂ ratios of partial melts are so source-dependent they are not considered a significant constraint in this study; TiO₂ and K₂O contents can be increased or decreased in a peridotite bulk composition without affecting phase relations significantly. High Al₂O₃/TiO₂ and CaO/TiO₂ ratios and low TiO₂ contents could be produced by high degrees of partial melting of a relatively fertile source or a low degree of partial melting of a relatively depleted source. Broadly speaking high Al₂O₃/TiO₂, CaO/TiO₂, low TiO₂, and K₂O indicate relatively depleted sources.

Results

All the equilibrium partial melt compositions from MORB pyrolite were subjected to simple incremental olivine fractionation calculations using increments of 0.1 wt.% olivine. At each step the equilibrium olivine was determined using a $(K_D)_{Fe/Mg}^{ol/liq} = 0.3$, with *mg*-number calculated on the basis of a $Fe^{2+}/(Fe^{3+} + Fe^{2+})$ ratio equal to 0.9. Several equilibrium partial melts from MORB pyrolite produced successful matches between calculated daughter liquids and primitive MORB glasses as indicated in Fig. 6. Partial melt compositions from pressures above 25 kb did not produce successful matches, as calculated derivative liquids become too Al₂O₃ and CaO rich when compared to primitive MORB glasses of similar *mg*-number. Partial melt compositions at less than 15 kb did not produce good matches for most primitive MORB glass compositions as calculated liquid compositions become too aluminous compared to primitive MORB glasses at a similar *mg*-number. Partial melts from MPY-87 at 20 kb produced successful matches, but FeO contents of calculated derivative liquids were too high compared to most primitive MORB glasses at a similar *mg*-number. Because the CIPW molecular norm calculation 'masks', Fe/Mg variation, it is possible to recalculate the Fe/Mg ratio of the partial melts (keeping the molecular total of Fe + Mg constant), without changing its molecular norm. Closer matches with the primitive MORB glasses were obtained in this way. Olivine subtraction calculations performed on the equilibrium melt compositions suggest that the majority of primitive MORB glasses can be produced from between 11–25 wt.% olivine fractionation, from primary magmas segregating from a MORB source diapirs at pressures of between 25 and 15 kb, with between 17 and 30 wt.% partial melting of the MORB pyrolite composition, leaving lherzolite and harzburgite residues. The harzburgite residues would recrystallize to lherzolite during subsolidus recrystallization at low pressures, because of high CaO and Al₂O₃ in residual orthopyroxene.

Although olivine fractionation is required to explain the composition of most MORB glasses, some primitive MORB glasses have major element compositions compatible with them being near-primary melts. Four examples are given in Table 6 and plotted in Fig. 6. T3-71D 159-10C1 (Table 6, no.4) is from the mid-Atlantic ridge at 29° 47'N (Keays & Scott,

TABLE 6
Primary MORB compositions

	1	2	3	4
SiO ₂	51.33	50.48	48.26	47.28
TiO ₂	0.61	0.87	0.89	0.97
Al ₂ O ₃	15.60	15.33	16.80	14.48
FeO	7.86	8.36	9.32	10.98
MnO	0.00	0.15	0.17	0.19
MgO	8.97	10.72	10.48	12.52
CaO	13.48	11.84	11.23	10.78
Na ₂ O	1.42	1.88	2.40	2.38
K ₂ O	0.05	0.17	0.03	0.04
P ₂ O ₅	0.03	0.09	0.06	0.09
Total	99.35	99.80	99.64	99.71
mg-no.	0.69	0.72	0.69	0.69
<i>CIPW norm (molecular)</i>				
Qz	8.39	0.00	0.00	0.00
Ab	10.53	14.39	17.65	16.98
An	29.79	28.05	28.66	22.74
Di	25.31	21.21	16.66	19.31
Hy	22.73	23.52	6.16	1.84
Ol	0.00	8.01	26.70	34.73
CaO/Al ₂ O ₃	0.86	0.77	0.67	0.74
CaO/Na ₂ O	9.49	6.29	4.68	4.53
CaO/TiO ₂	22.09	13.61	12.61	11.11
Al ₂ O ₃ /TiO ₂	25.57	17.62	18.87	14.93

(1) primitive MORB glass 212 (Melson *et al.*, 1976).

(2) *P*₂, most primitive olivine basalt from FAMOUS (Le Roex *et al.*, 1981).

(3) primitive MORB glass CH21-D20-29 (Basaltic Volcanism Study Project, 1981).

(4) primitive MORB glass T3-71D 159-10C1 (Keays & Scott, 1976).

mg-number and CIPW norm calculated on basis of $Fe^{2+}/(Fe^{2+} + Fe^{3+}) = 0.9$.

1976). In Fig. 8 T3-71D 159-10C1 plots close to the 20 kb olivine + orthopyroxene + clinopyroxene + liquid cotectic defined by equilibrium partial melts from MPY-87, and is similar in major element chemistry. CH21 D20-29 is a primitive MORB glass reported in the Basaltic Volcanism Study Project (1981), this composition plots close to the 15 kb olivine + orthopyroxene + clinopyroxene + liquid cotectic of MPY-90-40 and again is similar in major element chemistry to the 15 kb partial melts from MPY-90-40. *P*₂ is the average primitive olivine basalt composition of Le Roex *et al.* (1981) for the olivine basalts from the FAMOUS area. This composition plots on a olivine + orthopyroxene + clinopyroxene + liquid cotectic at 10 kb and is very close in composition to the 10 kb partial melt compositions reported in Falloon & Green (1987). Primitive MORB glass 212 from Melson *et al.* (1977) is quartz normative and plots very close to a 8 kb olivine + orthopyroxene + clinopyroxene + liquid cotectic from MORB pyrolite. 212 however plots at higher normative Di than the 8 kb cotectic in Fig. 6 and has significantly higher CaO content and higher CaO/Al₂O₃ and CaO/Na₂O ratios than the 8 kb liquids from MORB pyrolite. The glass 212 however is similar in composition to 10 kb liquid compositions from the more depleted Iherzolite composition Tinaquillo Iherzolite (Falloon & Green, 1987). Thus 212 could be a near primary liquid composition derived by minor olivine fractionation from a

10-8 kb olivine + orthopyroxene + clinopyroxene + liquid cotectic from a more depleted peridotite than MORB pyrolite.

Comparison with MORB picrite compositions

A common objection to a picrite model for MORB petrogenesis is the lack of picrite, especially picrite glass compositions, amongst MORB dredge or borehole collections. However due to the efficiency of olivine fractionation, picrite primary compositions will be unlikely to survive unmodified. Experimental work of Stolper & Walker (1980) and Sparks *et al.* (1980) demonstrate that picritic melts would necessarily be denser than common evolved MORB, and would be trapped at the base of magma chamber where they would fractionate olivine and other phases to produce more common evolved MORB compositions. Although olivine phenocryst-rich MORBs have been documented from MORB settings, most workers have not considered whole-rock compositions as representative of liquid compositions but as olivine accumulates. However, by using the most magnesian olivine present in a picrite suite and using an appropriate olivine-liquid K_D , the FeO and MgO contents of the equilibrium liquid can be obtained (Irvine, 1977; Basaltic Volcanism Study Project, 1981; Francis, 1985, 1986). In most cases the equilibrium liquid is of picrite composition. So even though picritic compositions are rare, the presence of magnesian olivine phenocrysts and megacrysts implies the existence of such liquids. In Table 7 are listed picrite compositions from the MORB setting, all of which are in equilibrium with the most magnesian olivine in the respective rock or suite. Most are actual whole rock compositions the rest are calculated compositions based on olivine addition or subtraction. The picrite compositions in Table 7 are plotted in the CIPW molecular normative basalt tetrahedron in Fig. 7. The picrite compositions in terms of silica saturation fall within olivine control lines drawn from the extremities of the MORB glass field. Significantly the picrite compositions can explain the entire range of silica-saturation displayed by primitive MORB glasses via olivine fractionation. One picrite composition lies outside the control lines to the MORB field in Fig. 7, SD-7A (Table 7, no.8) from the east Pacific rise (Schrader *et al.*, 1979).

Using the melting grid of equilibrium melt compositions from MORB pyrolite and assuming the picrite compositions are close to or are primary MORB magmas, the picrite compositions in Table 7 represent magma segregation at pressures between 15 and 25 kb, in equilibrium with spinel lherzolite and harzburgite residues. In no case is garnet a residual phase. The range of depth of magma segregation is similar to that inferred from analysis of equilibrium liquids from MORB pyrolite.

Another common objection to picrite primary melts is the Ni content of primitive MORB glasses which should be lower than observed if the primitive MORB glasses are derived by olivine fractionation from picrite primary melts. This objection is based on experimentally determined olivine-liquid partition coefficients for Ni in synthetic systems (Sato, 1977; Hart & Davis, 1978). This objection is overcome if partition coefficients from experimental studies on natural basalts are used (Arndt, 1977; Bickle *et al.*, 1977; Clarke & O'Hara, 1979; Elthon & Ridley, 1979; Budahn, 1986) and if a more appropriate crystallization equation is chosen e.g., equilibrium crystallization (Budahn, 1986).

Comparison with compositions determined from trapped glass inclusions

The presence of trapped glass inclusions in early-crystallizing phases, olivine, spinel, and plagioclase phenocrysts in MORB, offers an opportunity to see through the effects of magma mixing, and crystal fractionation, helping to identify parental and primitive magma

TABLE 7
MORB picrite compositions

	1	2	3	4	5	6	7	8	9	10	11
SiO ₂	46.87	46.95	47.09	47.70	47.60	48.78	46.90	48.19	47.78	48.33	48.30
TiO ₂	0.79	0.77	0.75	0.63	0.58	0.63	1.13	0.83	0.86	0.74	0.60
Al ₂ O ₃	16.51	16.59	16.84	13.72	13.80	15.7	12.60	14.12	14.50	11.35	13.70
FeO	10.47	9.65	9.69	9.45	9.37	7.96	10.16	9.22	9.07	10.19	7.90
MnO	0.17	0.16	0.17	0.16	0.18	0.15	0.18	0.14	0.14	0.17	0.12
MgO	52.1	11.60	11.29	15.80	14.80	12.32	16.40	15.32	13.27	17.70	16.90
CaO	10.11	11.16	11.29	10.14	10.70	12.61	10.30	10.19	10.64	9.57	10.90
Na ₂ O	2.13	2.15	2.19	2.07	1.84	1.55	2.00	1.41	2.19	1.34	1.65
K ₂ O	0.06	0.04	0.02	0.12	0.10	0.09	0.20	0.02	0.06	0.11	0.01
P ₂ O ₅	0.04	0.05	0.04	0.04	0.05	0.05	0.00	0.14	0.13	0.06	0.06
Cr ₂ O ₃	—	—	—	0.13	—	—	—	—	—	0.25	—
NiO	—	—	—	—	—	—	—	—	—	0.09	—
LOI	—	0.32	0.45	—	—	—	—	0.41	0.26	—	—
Total	100.16	99.44	99.82	99.96	99.02	99.91	99.87	99.90	98.90	99.90	99.94
mg-no.	0.69	0.70	0.69	0.77	0.76	0.76	0.76	0.77	0.74	0.78	0.81

	CIPW norm (molecular)									
Ne	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ab	15.05	14.52	14.11	12.93	11.40	12.95	9.20	14.78	9.23	11.36
An	27.81	26.72	26.14	21.11	22.79	29.35	18.43	23.37	22.22	18.89
Di	15.23	14.70	14.27	16.90	18.52	21.66	19.52	12.72	16.82	17.22
Hy	0.92	2.69	1.49	3.68	7.47	13.48	0.00	20.13	6.76	19.90
Ol	36.95	31.25	31.22	40.41	34.82	20.61	43.47	21.89	29.56	30.42
CaO/Al ₂ O ₃	0.67	0.67	0.67	0.73	0.77	0.79	0.82	0.72	0.73	0.84
CaO/Na ₂ O	5.20	5.20	5.15	4.89	5.81	8.13	5.15	7.23	4.86	7.14
CaO/TiO ₂	14.01	14.49	15.05	16.09	18.45	20.01	9.11	12.27	12.37	12.93
Al ₂ O ₃ /TiO ₂	20.89	21.54	22.45	21.77	23.79	25.03	11.15	17.01	16.86	15.34

- (1) TR123 4D-5 (Schilling *et al.*, 1983).
 - (2) TR123 4D-7 (Schilling *et al.*, 1983).
 - (3) TR123 4D-9 (Schilling *et al.*, 1983).
 - (4) calculated primitive liquid (Irvine, 1977).
 - (5) calculated parental magma composition (Ramsay *et al.*, 1984).
 - (6) calculated parental magma composition P₁ (Le Roex *et al.*, 1981).
 - (7) SO12 88-1 (Eissen *et al.*, 1981).
 - (8) SD-7A (Schrader *et al.*, 1979).
 - (9) SD-7B (Schrader *et al.*, 1979).
 - (10) calculated parental composition (Beets *et al.*, 1982).
 - (11) primary MORB picrite DSDP3-18-7-1 + 17wt.% olivine (Green *et al.*, 1979).
- CIPW norm and *mg*-number calculated on the basis of Fe²⁺/(Fe²⁺ + Fe³⁺) = 0.9.
- (—) not determined.

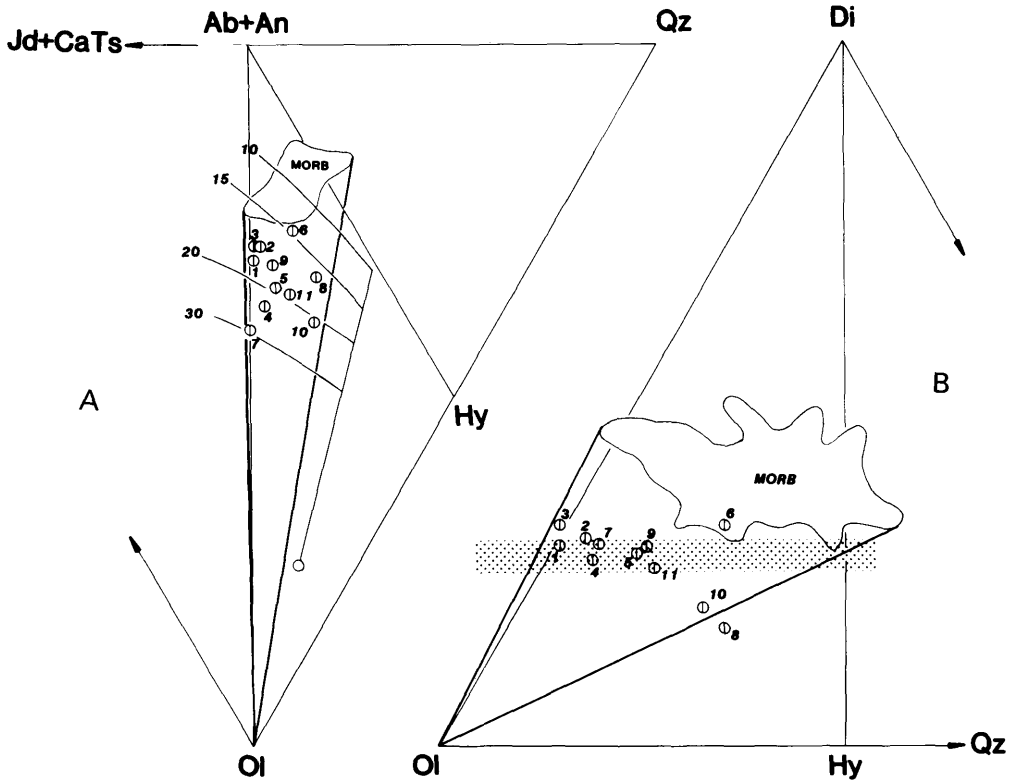


FIG. 7. MORB picrite compositions compared with equilibrium partial melts from MORB pyrolite and primitive MORB glasses in the CIPW molecular normative basalt tetrahedron projected from Di onto the base jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz (Qz)-olivine (Ol) in A, and projected from plagioclase (Ab + An) onto the face diopside (Di)-quartz (Qz)-olivine (Ol) in B. (○) MORB pyrolite, (⊙) numbered 1 to 11 are MORB picrite compositions from Table 7. Lines and cotectics as for Fig. 6.

compositions. The only problem with this approach is to see through the effects of post-entrapment interaction between the host mineral and the glass inclusion. In Table 8 are listed compositions of trapped glass inclusions where the effects of post-entrapment processes have been minimal or have been taken into account. The inclusion compositions are compared with primitive MORB glasses in the projection from Di and plagioclase (An + Ab) in Fig. 8. The glass inclusion compositions are all primitive, with high *mg*-number (0.68–0.78). In the projection from Di most of the inclusions plot within or close to the primitive MORB glass compositions (Fig. 8(a)). However glass inclusions from calcic plagioclase phenocrysts from the southwest Indian ridge (Price *et al.*, 1986) plot away from the primitive MORB glasses due to their high MgO contents (13.70–14.20 wt.%). In the projection from plagioclase (An + Ab), glass inclusions can be separated into two groups, which are discussed separately below:

(1) Glass inclusions plotting with primitive MORB glasses. Glass inclusions reported by Donaldson & Brown (1977), Dungan & Rhodes (1978), and Fujii & Fujioka (1978) plot within the primitive MORB glass spectrum. However, the composition of the inclusions are unlike any primitive MORB glass in low Al_2O_3 contents (14.21–14.50 wt.%) and high CaO/Al_2O_3 ratios (0.83–0.94). The difference between the primitive glass compositions and MORB compositions is evidence for processes of magma mixing occurring amongst MORB

TABLE 8
Compositions of primitive MORB glass inclusions

	1	2	3	4	5	6	7	8
SiO ₂	50.57	49.38	50.30	49.61	49.58	50.26	49.41	49.32
TiO ₂	0.54	0.64	1.20	0.86	0.65	0.61	0.54	0.24
Al ₂ O ₃	15.39	15.71	14.50	14.28	14.43	14.21	14.37	13.96
FeO	7.88	7.84	8.80	9.39	8.19	6.82	8.06	7.91
MnO	0.16	0.00	0.16	0.13	0.00	0.10	0.18	0.16
MgO	10.41	12.04	10.10	10.00	11.64	11.89	13.70	14.20
CaO	12.83	12.68	12.10	11.89	12.89	13.46	10.90	11.03
Na ₂ O	1.44	1.44	2.50	2.21	1.70	1.42	2.55	2.31
K ₂ O	0.03	0.08	0.05	0.07	0.03	0.07	0.03	0.03
P ₂ O ₅	—	—	—	—	0.04	—	—	—
Cr ₂ O ₃	—	—	—	0.06	—	—	0.09	—
Total	99.25	99.81	99.71	98.50	99.15	98.84	99.83	99.16
mg-no.	0.72	0.75	0.69	0.68	0.74	0.77	0.77	0.78
<i>CIPW norm (molecular)</i>								
Ab	11.31	10.77	18.66	16.85	12.77	10.84	17.96	16.41
An	31.01	30.14	23.44	24.49	26.50	27.39	21.72	21.87
Di	24.68	22.28	26.46	25.60	26.81	29.42	20.72	21.43
Hy	29.18	18.87	10.78	14.75	16.21	21.83	3.72	6.17
Ol	0.70	14.43	15.52	13.77	14.34	7.09	32.90	32.10
CaO/Al ₂ O ₃	0.83	0.81	0.83	0.83	0.89	0.94	0.75	0.79
CaO/Na ₂ O	8.91	8.80	4.84	5.38	7.58	9.47	4.27	4.77
CaO/TiO ₂	23.76	19.81	10.08	13.82	19.83	22.06	20.18	45.96
Al ₂ O ₃ /TiO ₂	28.50	24.55	12.08	16.60	22.20	23.29	26.61	58.16

- (1) Melt inclusion in Cr-spinel phenocryst (Le Roex *et al.*, 1981).
 - (2) Melt inclusion in Cr-spinel phenocryst (Le Roex *et al.*, 1981).
 - (3) Melt inclusion in olivine phenocryst (Fujii & Fujioka, 1978).
 - (4) Melt inclusion in plagioclase phenocryst (Dungan & Rhodes, 1978).
 - (5) Melt inclusion in olivine phenocryst (Dungan & Rhodes, 1978).
 - (6) Average melt inclusion in Cr-spinel (Donaldson & Brown, 1978).
 - (7) Melt inclusion in plagioclase phenocryst (Price *et al.*, 1986).
 - (8) Melt inclusion in plagioclase phenocryst (Price *et al.*, 1986).
- mg-number and CIPW norm calculated on the basis of $Fe^{2+}/(Fe^{3+} + Fe^{2+}) = 0.9$.
(—) not determined.

suites (Dungan & Rhodes, 1978). The glass inclusions although not primary melt compositions are very similar in composition to equilibrium partial melts from the relatively depleted Tinaquillo lherzolite composition. The glass composition identified by Donaldson & Brown (1977) could be derived from a 15 kb olivine + orthopyroxene + clinopyroxene + liquid cotectic from Tinaquillo with minor olivine fractionation.

(2) Glass inclusions plotting at more olivine rich compositions than primitive MORB glasses. These glass inclusions are possible primary melt compositions. Glass inclusions in Cr-spinel phenocrysts from the FAMOUS area (Le Roex *et al.*, 1981) plot in a similar position to 8 (no.1 Table 8) and 12 kb (no.2 Table 8) olivine + orthopyroxene + clinopyroxene + liquid cotectics from MORB pyrolite in both projections from Di and plagioclase (Ab + An) and have similar major element contents to the equilibrium partial melts from MORB pyrolite. Similarly to two MgO-rich glass inclusions reported by Price *et al.* (1986) from the western Indian Ocean (Table 8, no.s 7, 8) plot in a similar position to a 18 kb olivine + orthopyroxene + clinopyroxene + liquid cotectic from MORB pyrolite, and are similar in major element composition to the equilibrium partial melts from MORB pyrolite.

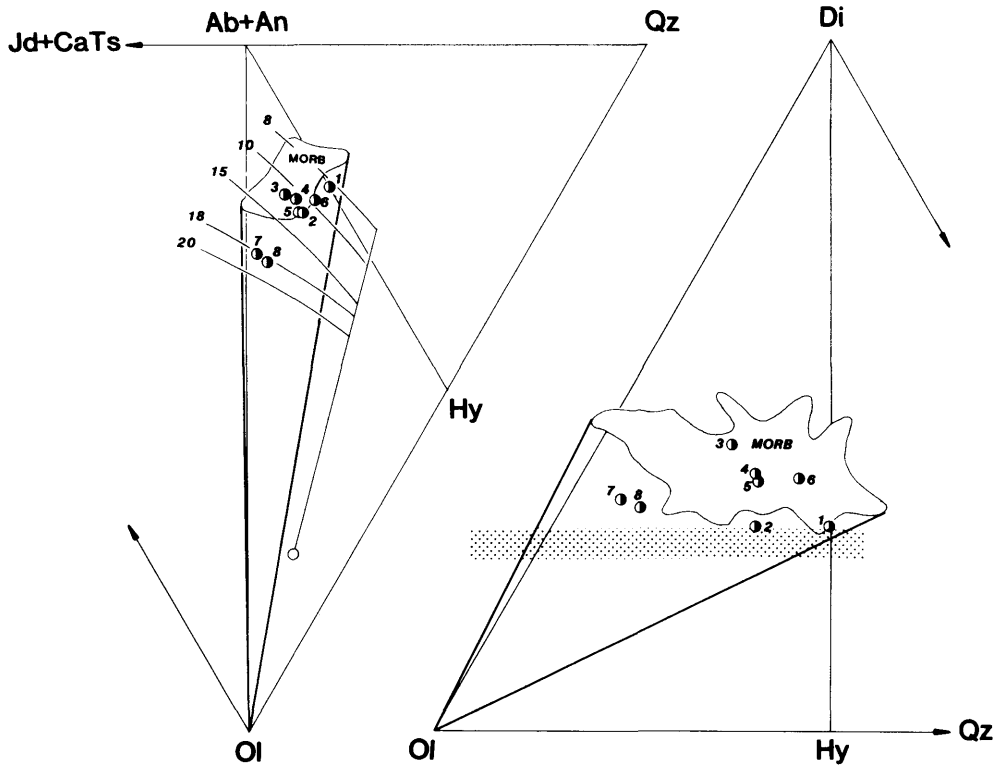


FIG. 8. The compositions of primitive MORB glass inclusions compared to equilibrium partial melt compositions from MORB pyrolite and primitive MORB glasses in the CIPW molecular normative basalt tetrahedron projected from diopside onto the base jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz (Qz)-olivine (Ol) in A, and from plagioclase (Ab + An) onto the face olivine (Ol)-diopside (Di)-quartz (Qz) in B. (●) numbered 1 to 8 are primitive MORB glass inclusions from Table 8, (○) MORB pyrolite. Lines and cotectics as for Fig. 6.

In summary amongst primitive glass inclusions from MORB are primary magmas from 8 to 18 kb based on a MORB pyrolite mantle source. The glass inclusions as well as the presence of calcic plagioclase and magnesian diopside megacrysts (Duncan & Green, 1980, 1987) provide evidence of primary melt compositions from more depleted mantle sources represented by Tinaquillo lherzolite. Such compositions are obscured amongst MORB glass compositions due to the processes of magma mixing (Donaldson & Brown, 1978; Dungan & Rhodes, 1978).

PRIMARY MORB MAGMAS

The results of the melting study on MORB pyrolite and Tinaquillo lherzolite suggests that primary magmas parental to common MORB segregate from upwelling mantle peridotite at pressures of between approximately 8 and 25 kb. Primary MORB melt compositions range from alkali-rich, slightly ne-normative picrites, to olivine-hypersthene picrites, to olivine and quartz normative tholeiites. The overwhelming majority of primitive MORB glasses are not primary magmas at 10 kb pressures (Falloon & Green, 1987) but are the result of olivine fractionation (11–25 wt.%) from primary magma formed between the pressures of 15–25 kb. However amongst the range of primitive MORB glass compositions that are primary or near primary magmas at 8 to 20 kb. The compositions of some primitive MORB glasses and

glass inclusions requires that more depleted source compositions than MORB pyrolite are present.

DISCUSSION

The results of this study are in agreement with previous workers who have suggested that there exists a spectrum of primary MORB magma compositions (Bryan *et al.*, 1981; Maaløe & Hansen, 1982; Grove & Bryan, 1983; Christie & Sinton, 1986; Francis, 1986; Klein & Langmuir, 1987; Thompson, 1987). The results of this study are not in agreement with models which suggest that primary magmas are represented by the most primitive MORB glasses (Green & Ringwood, 1967; Presnall *et al.*, 1979; Fujii & Bougault, 1983; Fujii & Scarfe, 1985). Three other studies have used larger data bases for the discussion of the petrogenesis of MORB and it is therefore important to compare the results of this study with these other studies. Klein & Langmuir (1987) have studied MORB major element systematics on a global basis, by correcting for crystal fractionation and comparing different MORB suites at an MgO content of 8 wt.%. Klein & Langmuir (1987) have demonstrated a strong negative correlation between FeO, Na₂O contents, and CaO/Al₂O₃ ratios with axial depth on a global scale. By applying the continuous melting model of McKenzie (1984) this global correlation can be explained by 'mean' melting intervals of 5 to 15 kb. In the model of Klein & Langmuir (1987) picrite primary melts with > 17 wt.% MgO are not important in the generation of MORB, but primary magmas of between 10–17 wt.% MgO are more dominant.

Klein & Langmuir (1987) suggest that a temperature variation of over 200°C is required within upwelling oceanic mantle to account for the range in MORB compositions. This temperature interval agrees with the suggested range of temperatures of primary melts generated from a MORB pyrolite composition (1350–1550°C). The composition of primary melts generated during a continuous melting process will be substantially different from equilibrium batch partial melts present in this paper. It is clear however both from the major element composition of primitive MORB glasses and MORB compositions on a global scale (Klein & Langmuir, 1987) that they preserve a history of magma segregation from depths of a least 25 kb. If a continuous melting process involving small melt fractions is involved then some mechanism is required to preserve picritic primary melt compositions from 20 to 25 kb, from being mixed into other melt fractions from shallower depths in the melting column (see Thompson, 1987 for further discussion of this problem). Even if continuous melting is the most physically correct model, melt compositions would still be constrained to lie on olivine + orthopyroxene ± clinopyroxene + liquid cotectics and therefore still plot below primitive MORB glasses in the projection from plagioclase (Ab + An) in the basalt tetrahedron. Thus a range of olivine fractionation is still required to produce primitive MORB glasses. A more detailed discussion of the implications of dynamic melting models (McKenzie, 1984; McKenzie & Bickle, 1988) on MORB petrogenesis is presented in Falloon *et al.* (1988).

Takahashi *et al.* (1987) have used a different approach for determining primary magma compositions to MORB. Using experimentally determined K_D 's for CoO, MgO, FeO, NiO, and MnO for olivine and liquid, they have incrementally calculated the compositions of liquids in equilibrium with olivine until such stage as the calculated equilibrium olivine composition falls within the 'mantle array' for olivine in terms of NiO and MnO contents. This establishes the composition of the primary magma. Takahashi *et al.* (1987) suggest that primary magmas to MORB, range in MgO content from 11–16 wt.%. Representative calculated primary melt compositions from Takahashi *et al.* (1987) are plotted in Fig. 9 and are compared with primitive MORB glasses and equilibrium partial melts from MORB

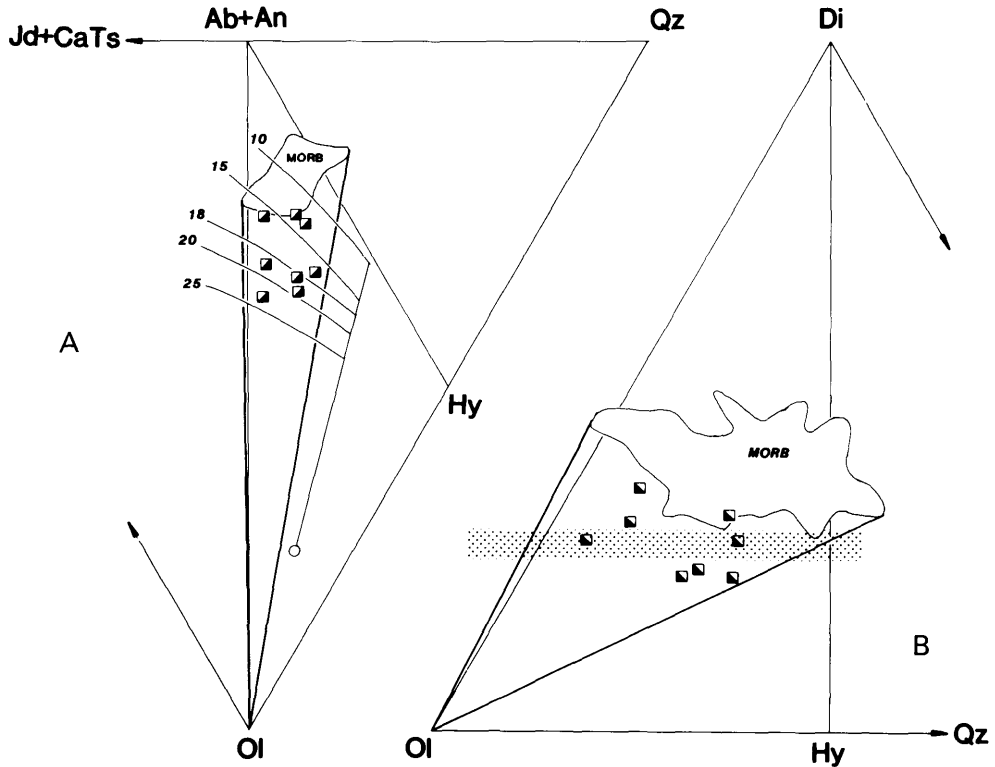


FIG. 9. Calculated primary MORB melt composition from Takahashi *et al.* (1987) compared with equilibrium partial melt compositions from MORB pyrolite and primitive MORB glasses in the CIPW molecular normative basalt tetrahedron projected from Di onto the base jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz (Qz)-olivine (Ol) in A, and from plagioclase (Ab + An) onto the face diopside (Di)-quartz (Qz)-olivine (Ol) in B. (○) MORB pyrolite, (■) calculated primary MORB melt compositions from Takahashi *et al.* (1987). Lines and cotectics as for Fig. 6.

pyrolite. The calculated compositions mostly plot away from the primitive MORB glasses, however in the plagioclase (Ab + An) projection, some plot close to the low Di end of the primitive MORB glasses. Compared to equilibrium partial melts from MORB pyrolite the calculated primary melts from Takahashi *et al.* (1987) represent magma segregation over pressures of 12 to 22 kb. The theoretical analysis of Takahashi *et al.* (1987) is in agreement with the experimental results from MORB pyrolite.

CASE STUDY IN MORB PETROGENESIS: FAMOUS-NARROWGATE-AMAR

The FAMOUS-NARROWGATE-AMAR (FNA) area at 36° 47'N on the mid-Atlantic ridge is one of the most thoroughly documented areas of the mid-Atlantic ridge and has provided a large amount of data on the nature and composition of MORB (Bougault & Hekinian, 1974; Hekinian *et al.*, 1976; Arcyana, 1977; Bryan & Moore, 1977; Langmuir *et al.*, 1977; White & Bryan, 1977; Bryan, 1979; Bryan *et al.*, 1979; Le Roex *et al.*, 1981; Stakes *et al.*, 1984). As most of the sampling was done by submersible dives there is good spatial and temporal control on the recovered lavas, not possible by dredging. Stakes *et al.* (1984) have demonstrated that the morphology of the rift valley area is dominated by either tectonic or volcanic processes, which are the result of the growth and solidification of ephemeral ridge-

axis magma chambers. The rift valley in the FAMOUS area is presently dominated by axial volcanic highs represented by Mt Venus and Mt Pluto, whereas the rift valley in the AMAR area is dominated by normal faulting. Of importance is the distinction between the younger pillowed units forming the central volcanic highs (Mt Venus and Mt Pluto), and the older sheet and massive lava flow units forming the valley floors and exposed in the rift valley walls. The younger pillowed units are of dominantly primitive compositions containing minor amounts of olivine as the main phenocryst phase. These basalts are also characterized by having relatively high Ni contents in olivine phenocrysts compared with the older series lavas (Le Roex *et al.*, 1981; Nabelek & Langmuir, 1986). The older sheeted and massive flows, from the valley floors and walls, are characterized by more evolved compositions and include picritic basalts (found only on the valley floor near Mt Venus, Hekinian *et al.*, 1976), plagioclase–pyroxene–olivine-phyric basalts, plagioclase-phyric basalts, and aphyric basalts. These basalts belong to a low-Ni series due to low Ni in olivine phenocrysts, for a given Mg/Fe content, relative to the younger pillowed lavas (Le Roex *et al.*, 1981; Nabelek & Langmuir, 1986). Primitive glass compositions from these two distinctive series are plotted

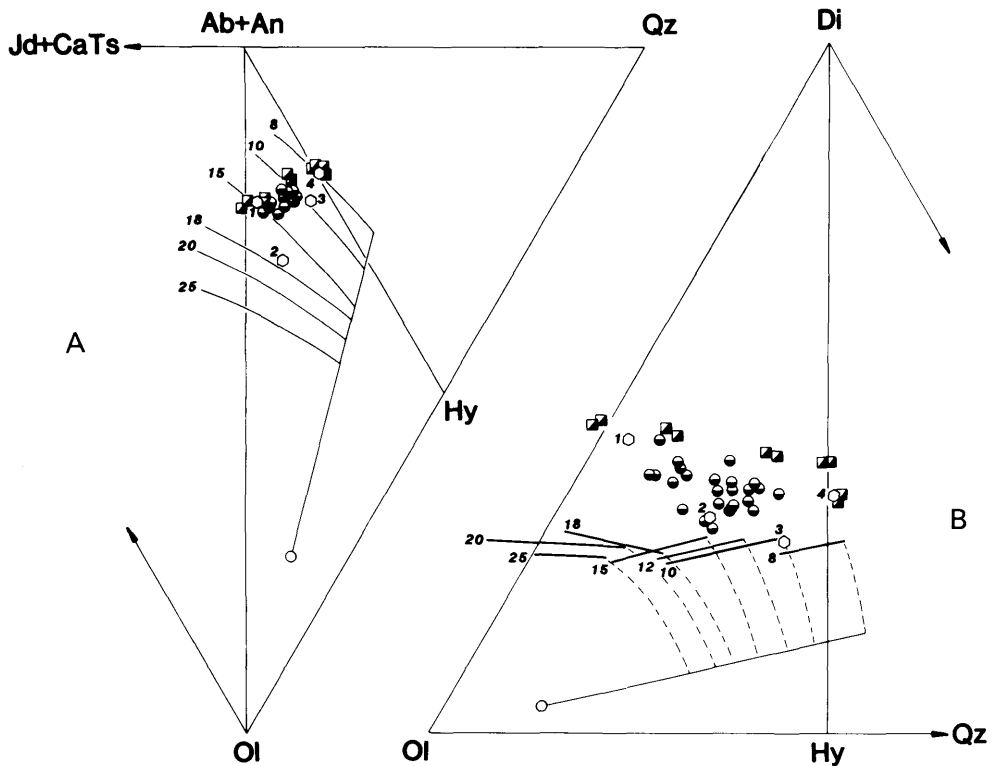


FIG. 10. Primitive glass compositions from the FAMOUS-NARROWGATE-AMAR area of the Mid-Atlantic ridge compared with equilibrium partial melt compositions from MORB pyroxite in the CIPW molecular normative basalt tetrahedron projected from Di onto the base jadeite plus calcium tschermak's molecule (Jd + CaTs)-quartz (Qz)-olivine (Ol) in A, and projected from plagioclase (Ab + An) onto the face diopside (Di)-quartz (Qz)-olivine (Ol) in B. (■) primitive glass compositions from the low-Ni series lavas (see Table 9 for data sources), (●) primitive MORB glass compositions from the high-Ni series lavas (see Table 9 for data sources), (○) numbered 1 to 4 are as follows: (1) high-olivine parental composition (Bryan, 1979), (2) calculated parental magma composition to FAMOUS picrite basalts P_1 (Le Roex *et al.*, 1981), (3) primitive olivine basalt composition P_2 (Le Roex *et al.*, 1981), (4) low-olivine parental composition (Bryan, 1979). In A lines are cotectics from MORB pyroxite as for Fig. 6, in B cotectics as for Fig. 2.

TABLE 9
Glass compositions from the Famous-Narrowgate-Amar lava series

	<i>Olivine basalts High-Ni series</i>	<i>Picrite basalts low-Ni series</i>	<i>Fracture Zone A</i>
SiO ₂	48.20–50.48	48.75–51.40	48.20
TiO ₂	0.65– 0.85	0.63– 0.93	0.57
Al ₂ O ₃	15.23–16.70	14.80–16.60	16.95
FeO	8.04– 9.18	7.90– 8.46	8.50
MgO	9.43–10.70	8.82–10.50	10.00
CaO	11.56–12.50	12.70–13.79	12.75
Na ₂ O	1.94– 2.41	1.84– 2.01	2.32
K ₂ O	0.04– 0.16	0.05– 0.14	0.04

Data sources: Bryan (1979), Stakes *et al.* (1984), Bryan & Moore (1977), Hekinian *et al.* (1976), Langmuir *et al.* (1977), Fujii & Bougault (1983), Bender *et al.* (1978), Le Roex *et al.* (1981).

in the CIPW molecular normative basalt tetrahedron in Fig. 10. The range in major element composition of the two glass groups is summarized in Table 9. Primitive glass compositions from the low-Ni series are defined by glass from picrite basalts, glasses from Fracture zone A (Bryan, 1979), glasses from walls at the south and north valleys of the FAMOUS areas (Bryan, 1979), and primitive glass compositions identified from the Narrowgate and AMAR valleys (Stakes *et al.*, 1984). Also plotted are the high-olivine and low-olivine parental compositions from Bryan (1979), and the parental magmas to picritic basalts and olivine basalts from Le Roex *et al.* (1981). Glasses from the high-Ni series are all from Bryan & Moore (1977). Primitive glasses from Fracture zone A (Bryan, 1979) are distinctive in being slightly ne-normative. The low and high Ni series can be distinguished both in Fig. 10(a) and (b). The low Ni series is characterized by a large range in silica saturation and high CaO contents (Table 9). The high Ni series has lower CaO contents and a more restricted range in silica saturation. The high-olivine parental composition of Bryan (1979) is a hybrid of glasses from low and high Ni series glasses as well as Fracture zone A glasses. The low-olivine parental composition of Bryan (1979) is an average of primitive glasses from the low-Ni olivine series lavas.

Although two magma series have been identified in the FNA area, no single magma composition can be parental to an entire series as there is a large variation in TiO₂ contents and Na₂O/K₂O ratios at the high *mg*-number >0.68 end of the glass compositions from both series (Stakes *et al.*, 1984). The range in silica saturation displayed by the FAMOUS glasses also argues against a single parental magma type but could be consistent with an array or primary magmas arriving at the base of sub-axial magma chambers. Amongst the glass compositions there is evidence for decoupling of minor elements (TiO₂, K₂O, P₂O₅) from major elements suggesting open-system magma chamber and magma mixing processes are taking place (O'Hara & Mathews, 1981).

The low CaO contents of the high-Ni series glasses indicates that they have undergone little olivine fractionation from primary olivine tholeiite magmas. The range in silica contents in the high-Ni series glasses indicates that primary liquids segregated from a MORB pyrolite source at between approximately 18–20 to 10kb with little olivine fractionation (<10 wt. %). The primitive olivine tholeiite magma of Le Roex *et al.* (1981) is identical to 10kb equilibrium liquids from MORB pyrolite (Falloon & Green, 1987) and represents a 10kb primary olivine tholeiite liquid. However LeRoex *et al.* (1981) found that this composition was unsuitable to be parental to other more evolved olivine basalts in their study sample.

The low-Ni series glasses, including Fracture zone A glasses, are characterized by a large range of silica saturation indicating a larger range of partial melting (15–30 wt.%) with both lherzolite and harzburgite residues. The high CaO contents indicate relatively high degrees of olivine fractionation. Based on the equilibrium liquids from MORB pyrolite, depths of segregation of 20–25 kb are required to explain the low-Ni series glasses with between 20 and 25 wt.% olivine fractionation. It appears that during episodic periods of faster spreading, primary MORB magmas segregate from greater depths, result from a larger range of partial melting, and undergo greater amounts of olivine fractionation than during periods of slower spreading. During periods of faster spreading primary picrite melts are trapped at the base of steady-state magma chambers where they undergo crystal fractionation.

The depths of magma segregation determined for the two magma series at FNA agrees with the analysis of Klein & Langmuir (1987) and Nabelek & Langmuir (1986) concerning Ni-olivine relationships. Klein & Langmuir (1987) suggest that if MORB suites display differences in Ni, the suite with the lower Ni contents at a given MgO may be derived from parental magmas with higher MgO contents, derived from greater extents of melting at greater depth.

The parental magma for the picritic basalts (P_1) from Le Roex *et al.* (1981), in the projection from Di (Fig. 10(a)) falls on or near an 18 kb cotectic from MORB pyrolite. However in the projection from plagioclase (Ab + An) the composition P_1 plots above the 18 kb cotectic suggesting it is not a primary magma and has undergone some degree of olivine fractionation, possibly from a more picritic parent lying on a 20 or 25 kb cotectic.

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