

Residual Glasses and Melt Inclusions in Basalts From DSDP Legs 45 and 46: Evidence for Magma Mixing

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Abstract. Compositional relations among natural glasses in basalts recovered by Legs 45 and 46 (DSDP) provide powerful constraints on their differentiation histories. Residual glass compositions in the moderately evolved aphyric and abundantly phyrlic basalts within each site demonstrate that none of the units is mutually related to any other or to a common parent by simple fractional crystallization. At Site 396, where clinopyroxene phenocrysts are absent, progressively more evolved liquids (lower Mg/(Mg+Fe) and higher TiO₂) are characterized by lower calcium-aluminum ratios, which can only be generated by clinopyroxene fractionation. This paradox is amplified by some melt inclusions in olivine phenocrysts that have higher CaO/Al₂O₃ and lower TiO₂ than any residual glasses. The occurrences of these distinctive compositions are correlated with the highly magnesian character of the host olivines (Fo₉₀₋₈₉), and the melts are interpreted as trapped primitive liquids, parental to the more fractionated derivatives.

Melt inclusions intermediate in composition between the residual glasses and the most primitive olivine melt inclusions are present in the cores of some plagioclase phenocrysts that have had a history of resorption. On the basis of a petrographic and microprobe analysis of the zoning relations in these phenocrysts, the inclusions are inferred to be melts entrapped at the time of extensive corrosion of the host crystals.

Interpreted in conjunction with other mineral and geochemical data, the compositional trends in the

glasses indicate that magma mixing has played a major role in the genesis of the Leg 45 and 46 basalts. The reality of mixing is demonstrated by extensive disequilibrium textures in the plagioclase phenocrysts and the presence in evolved lavas of refractory plagioclase and olivine phenocrysts bearing primitive melt inclusions. The chemical imprint of clinopyroxene fractionation despite the absence of clinopyroxene phenocrysts is believed to be accomplished by plating of gabbro on to the upper walls of the subvolcanic magma chamber as it evolves between mixing events. Repeated influxes of primitive magma batches will move the resultant hybrids away from clinopyroxene saturation and generate olivine-plagioclase cotectic magmas. This model provides a physical buffering mechanism that accounts for the volumetric dominance of moderately evolved basalts among ocean floor tholeiites. Major and trace element models based on the combination of mixing and fractional crystallization also explain heretofore enigmatic geochemical characteristics of MORB.

Introduction

Natural glasses in ocean floor basalts, occurring both residually in pillow rinds and as inclusions in phenocrysts, provide extremely useful samples of magmatic liquids which are potential recorders of the entire differentiation histories of these rocks. This appears to be the case for the Site 395 and 396 basalts. The analyses of natural glasses and the accompanying discussion of their bearing on our understanding of MORB differentiation presented in this paper are part of a comprehensive geochemical and petrologic study of basalts recovered by drilling in Legs 45 and 46 of DSDP. By collecting multiple types of mineral

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and bulk rock chemical data on the same suite of samples, we have sought to provide a matrix of constraints from which new insights into ocean floor basalt petrogenesis can be derived.

Recent studies of ocean floor basalt petrogenesis have attempted to explain the variations among the observed lavas largely in terms of melting a mantle source followed by low-pressure crystal fractionation (Kay et al., 1970; Schilling, 1971; Frey et al., 1974; Bryan et al., 1976; Langmuir et al., 1977). The rather uniform major and trace element compositions, restricted mineralogy, and the absence of complications associated with eruption through continental crust, make the ocean floor basalts a fruitful area for applying simple genetic models. However, the results of rigorous studies have shown that the generalizations initially developed do not explain all the details of compositional variation in ocean floor basalt suites. Indeed, the discrepancies between predictions based on these models and the natural systems are quite consistent and suggest that some process other than crystal fractionation or partial melting is operating systematically to generate the apparent geochemical anomalies. Modeling of fractionation relations among temporally and spatially associated basalts, which appear to have been erupted from the same vent system and which have trace element characteristics consistent with derivation from the same mantle source, demonstrates that these basalts cannot be related by any simple scheme involving fractionation of phenocrysts in their observed modal abundances. An alternative explanation is that each basalt unit has been generated independently from a heterogeneous mantle and has subsequently undergone a separate and distinct fractionation history (e.g., Blanchard et al., 1976; Bryan et al., 1976; Rhodes et al., 1976; Bryan and Moore, 1977).

We have shown on the basis of extensive evidence of crystal-liquid disequilibrium in the Leg 45 and 46 basalts that they are products of mixing evolved and primitive basalts (Dungan et al., 1977; Dungan et al., 1978a and b; Rhodes et al., 1978b). The glass data provide critical constraints on the nature of the liquids that were mixed, including the composition of the parental magma.

Analytical Technique

A total of 89 microprobe analyses (11 elements) of natural residual glasses and glass melt inclusions were performed with a 3 channel ARL-EMX instrument. Analyses were made in four separate passes. Residual glasses in thin sections of pillow rinds were made by randomly choosing 10–15 points in crystal-free areas. Counting time for each point was 20 s for K–Ca–Na and 30 s for Si–Fe–Mg, Ti–P–Al and Cr–Mn. Beam size was 20–30 μm . Generally

fewer points were averaged for melt inclusion analyses due to their size (<150 μm).

Residual glasses were found to be homogeneous and glasses in the margins of pillows of aphyric lavas closely approach bulk XRF analyses for the same pillow rinds. The glasses have slightly lower $\text{Mg}/(\text{Mg} + \text{Fe}^{+2})$ compared to the XRF data, as we would expect. However, the CaO-contents of glasses as measured by microprobe are slightly higher than in the XRF analyses. All other oxides are identical within analytical uncertainty. Glass analyses reported here are the same as those which appear in Dungan et al. (1978b).

Petrology and Geochemistry of the Leg 45–46 Basalts

Legs 45 and 46 of the Deep Sea Drilling Project (DSDP) succeeded in drilling four holes (395, 395A, 396, 396B) at two sites in young oceanic crust in the vicinity of the mid-Atlantic ridge at about 22° N. They are approximately symmetrically disposed relative to the ridge axis in mid- to late-Miocene basement (7–10 m.y.). Total penetration in basement was 1019 m with the deepest hole being 576 m at 395A. The basalts sampled at these two sites formed at nearly the same latitude on the ridge crest and subsequently moved about 150 km away from the axis of accretion.

Figure 1 is a generalized summary of the stratigraphic relations at the two sites, each of which includes a shallow, single-bit hole and a deeper hole achieved by multiple reentry techniques. At both sites two petrographically distinct basalt types are inter-layered. In all four holes there are basalts that are essentially aphyric and others that contain abundant phenocrysts of plagioclase and olivine.

At both sites pillowed basalts predominate in the cored sections. However, both massive cooling units and clastic breccias are present (Leg 46 Shipboard Party, 1976). A thick sill (Unit P4') and several massive units make up the bulk of the aphyric basalts at Site 395, and Unit A₃ (Site 396B) is a massive cooling unit with a thin pillowed carapace. No glassy material was recovered from the base of the unit. As a result of the lower abundance of glassy pillow rinds at Site 395, our collection of glasses from Hole 396B is much more extensive.

Petrography of Aphyric Basalts

The most abundant type (Fig. 1) consists of the so-called aphyric basalts, which lack megascopic phenocrysts. Microphenocrysts of olivine (Units A₂, A₄-395) or olivine and plagioclase (all other aphyric units) are abundant in the glassy pillow rinds, and some of the units contain large (>1 mm) anhedral, corroded crystals of olivine and plagioclase. These crystals exhibit both chemical and textural incompatibility with their host liquids. Clinopyroxene

microphenocrysts are entirely absent from relatively evolved aphyric basalts at both sites but two examples of gabbroic inclusions have been recognized in aphyric rocks of 396B (Sato et al., 1978 and Flower et al., 1978). These appear to be wall rock xenoliths.

The following lines of evidence indicate that chemical analyses of fresh samples of aphyric rocks closely correspond to liquid compositions:

1. The low modal abundance ($\approx 1-5\%$) and small size ($\approx 100 \mu\text{m}$) of the microphenocrysts and their typically skeletal morphology indicate that they grew in place during or just prior to eruption (Donaldson, 1976). Consequently they cannot have undergone redistribution subsequent to their crystallization.

2. Glass compositions in aphyric rocks are very close to those of the freshest bulk rock analyses from the same units. Elements that are not subject to transport during alteration show very little variation within individual rock units, and where several glass analyses are available from a single unit (e.g., A₂, C-396B) the variations are well within analytical error (Table 1).

3. One-atmosphere melting experiments on three of the aphyric rocks (Dungan et al., 1978a and b) demonstrate that the naturally occurring microphenocrysts are the low pressure liquidus phases of these rocks.

4. Coexisting olivine microphenocryst-residual glass pairs have been analyzed by microprobe in aphyric and phyric pillow rinds in 25 of the Leg 45-46 basalts. These yield a K_D of 0.27 for iron-magnesium partitioning (Roeder and Emslie, 1970) between olivine and liquid (Dungan et al., 1978b). The close correspondence of these data to a single equilibrium K_D corroborates the petrographic

interpretation of crystallization from liquids corresponding to the present bulk rock compositions. Calculations of equilibrium plagioclase compositions using natural glass compositions, temperatures derived from the one-atmosphere experiments and the expression developed by Drake (1976) show good agreement with natural microphenocryst compositions (Rhodes et al., 1978b). The large ($> 1.5 \text{ mm}$) "xenocrysts" of olivine and plagioclase that occur sporadically (volume $< 1\%$) in several of the aphyric units are texturally and chemically out of equilibrium with their host liquids. Generally they are more magnesian or calcic respectively than the microphenocrysts. Petrographically the disequilibrium is recognized by the typical anhedral shapes and in some cases textural evidence of resorption.

Petrography of Phyric Basalts

The phyric basalts at Sites 395-396 contain up to 30% of plagioclase and olivine phenocrysts, with plagioclase being the more abundant phase by a factor of at least two. These rocks also contain minor spinel as microphenocrysts in the groundmass and as inclusions in olivine and plagioclase. Spinel is more abundant in Unit B-396B than in any of the Site 395 phyric basalts but the compositional ranges are very similar. Clinopyroxene is a minor phenocryst phase in the phyric basalts only at Site 395. It is entirely absent from 396B phyric lavas. One-atmosphere melting experiments on two of the phyric basalts show that plagioclase is alone

Table 1. Average compositions of residual glasses of five units in Hole 396B

	A ₁ (3)	A ₂ (10)	A ₃ (1)	B (8)	C (8)
SiO ₂	50.38 ± 0.13	50.63 ± 0.19	50.20	50.59 ± 0.17	49.75 ± 0.12
TiO ₂	1.35 ± 0.03	1.47 ± 0.02	1.58	1.29 ± 0.09	1.47 ± 0.02
Al ₂ O ₃	15.19 ± 0.02	14.97 ± 0.01	15.08	15.02 ± 0.10	15.62 ± 0.05
Cr ₂ O ₃	0.05 ± 0.01	0.04 ± 0.01	0.05	0.05	0.04 ± 0.01
FeO ^a	9.43 ± 0.01	9.71 ± 0.06	9.91	9.42 ± 0.32	9.39 ± 0.03
MnO	0.17 ± 0.01	0.18 ± 0.01	0.17	0.18 ± 0.01	0.17 ± 0.01
MgO	8.03 ± 0.02	7.85 ± 0.06	7.26	7.79 ± 0.16	7.78 ± 0.06
CaO	11.67 ± 0.06	11.39 ± 0.04	11.04	12.02 ± 0.14	11.39 ± 0.09
Na ₂ O	2.66 ± 0.03	2.77 ± 0.03	2.96	2.69 ± 0.05	2.89 ± 0.03
K ₂ O	0.12 ± 0.01	0.13 ± 0.04	0.12	0.11 ± 0.01	0.19 ± 0.01
P ₂ O ₅	0.14 ± 0.01	0.14 ± 0.01	0.17	0.12 ± 0.02	0.16 ± 0.01
Total	99.19	99.28	98.44	99.28	98.85
Mg'	0.627	0.616	0.592	0.621	0.622
CaO/Al ₂ O ₃	0.768	0.761	0.732	0.800	0.730
CaO/Na ₂ O	4.4	4.1	3.7	4.5	3.9
or	0.71	0.77	0.71	0.71 - 0.65	1.12
ab	22.51	23.52	25.05	23.10 - 22.26	23.69
an	29.15	27.99	27.51	28.05 - 29.24	29.49
di	22.82	22.61	21.50	24.40 - 24.93	21.32
hy	14.36	15.10	13.86	13.40 - 13.34	10.60
ol	5.30	4.69	4.98	5.26 - 5.01	7.95
mg	1.52	1.57	1.59	1.58 - 1.45	1.51
chr	0.06	0.06	0.07	0.07 - 0.07	0.06
il	2.56	2.79	3.00	2.62 - 2.18	2.79
ap	0.28	0.33	0.37	0.26 - 0.22	0.33

^a Norm for A₁, A₂, and C are averages. The range shown for Unit B corresponds to individual norms for the most evolved and primitive glasses respectively

FeO* total iron expressed as FeO: Mg' = mol. prop. Mg/(Mg + Fe) adjusting Fe⁺³/Fe⁺² = 0.1

on the liquidus followed by olivine and spinel and then clinopyroxene (Dungan et al., 1978a and b).

The olivine and plagioclase phenocrysts in the phyric lavas are highly diverse in their compositions, textures and zoning patterns. The petrography and mineral chemistry are discussed in Dungan (1978a and b) and Dungan and Long (in preparation) and will not be treated in detail here. However, the diversity in zoning patterns and evidence for disequilibrium mineralogy in the phyric rocks is the primary evidence that these basalts are hybridized and do not represent liquid compositions. This conclusion is based on equilibrium relationships derived from the study of glass-microphenocryst pairs in the aphyric basalts (=liquids) and our one-atmosphere melting experiments. Relationships between mineral and bulk rock compositions are discussed below as they pertain to evidence of hybridization by magma mixing in the Site 395-396 phyric basalts.

The range of olivine compositions in glassy phyric basalts at both sites is $Fo_{90.5} - Fo_{83}$. A few of these phenocrysts are reversely zoned with cores of Fo_{83-84} and rims of Fo_{85-86} . Extrapolation of the olivine-liquid partition coefficient of 0.27 to the $Mg/(Mg + Fe^{+2})$ range of the phyric basalts (0.62-0.68) indicates that the most magnesian olivines in these basalts ought to be Fo_{85-88} . On the basis of these data, some of the phenocrysts are too forsteritic to have been in equilibrium with liquids corresponding to the bulk compositions of the rocks in which they are found. Olivine phenocrysts as magnesian as Fo_{90} occur in phyric basalts with $Mg/(Mg + Fe^{+2}) = 0.64$. These magnesian olivines are presumed to have been added to their present host liquids. The bulk compositions of these rocks are therefore skewed somewhat to higher $Mg/(Mg + Fe^{+2})$ by olivine accumulation, indicating that the present relationships are representative of the minimum degree of disequilibrium. Addition of only five percent of olivine (Fo_{88}) to one of our basaltic liquids with an $Mg/(Mg + Fe^{+2})$ of 0.56 results in a shift of the resultant hybrid to $Mg/(Mg + Fe^{+2}) = 0.64$. Assuming that the highly magnesian phenocrysts were carried in appropriately primitive liquids, quite profound disequilibrium is indicated.

Plagioclase phenocrysts in the phyric basalts exhibit evidence of disequilibrium analogous to the olivine phenocrysts. A few of the plagioclase phenocrysts are reversely zoned with resorbed cores mantled by more calcic overgrowths. The range of normally zoned plagioclase crystals is An_{86} to An_{68} in glassy basalts. Large equant phenocrysts and smaller laths with weakly zoned cores of An_{86-83} are typically rimmed by overgrowths of An_{74} to An_{70-68} . The one-atmosphere liquidus plagioclase in a phyric basalt from Hole 395 is An_{75-74} (Dungan et al., 1978a). Calculations of equilibrium plagioclase compositions using natural bulk rock compositions and Drake's (1976) equation do not show the close agreement with natural phenocryst compositions that the aphyric basalts do. However, the liquidus plagioclase in one-atmosphere experiments is very close to the composition predicted by the Drake-type calculations where the actual coexisting liquid is used in the calculations.

Geochemistry and Magmatic Stratigraphy

We have analyzed a suite of over 150 basalts from Sites 395 and 396 for major and trace elements and selected 50 rocks from this collection for trace element determinations by INAA. The complete lists of analyses are included in Rhodes et al. (1978a) and Dungan et al. (1978b). The tabular listing of glass analyses on which this paper is based appears in Dungan et al. (1978b).

On the basis of these 28-element analyses, the Leg 45 and 46 basalts are all moderately evolved tholeiites with major and trace element characteristics of typical MORB from normal ridge segments. The major element compositions are indicative of fractionated ocean floor basalts ($Mg/(Mg + Fe^{+2}) = 0.60-0.68$) but

highly evolved FeTi variants are absent. The aphyric basalts at each site have more evolved compositions and higher magmaphile element concentrations than any of the phyric lavas. The Site 395 basalts are somewhat more evolved on the average than those at 396 but a comparison of major and trace element analyses of basalts from the two sites indicates that they are very similar. In fact, ratios of magmaphile elements, which are not appreciably changed during fractional crystallization, show only slight variations within and between sites over a factor of two increase in elemental abundances. These basalts have low lithophile element contents ($Sm = 13-23 \times$ chondrites) and, with the exception of one unit (C-369B, see Fig. 1), the La/Sm ratios fall within the narrow range of 0.85-0.93 that is typical of LREE-depleted MORB. Thus it would appear that the mantle source rocks that were partially melted to give rise to the parental basalts of these moderately evolved lavas are homogeneous with respect to their trace element compositions.

The stratigraphic distribution of flow units (Fig. 1) indicates interlayering of aphyric and phyric basalts. Within the sequences of the two deep holes there are complex relationships between stratigraphic position and magma composition. The group of four phyric basalt units a 395A does not embody any systematic change in composition with stratigraphic position. The stratigraphically lowest and highest aphyric units in 395A (A_2 and A_4) are virtually identical in composition. The three aphyric units at the top of 396B exhibit a chemical progression from the most evolved unit at the base (A_3) upsection through less fractionated basalts (A_2 and A_1).

Phenocrysts are distributed heterogeneously throughout the phyric units. The lack of homogeneity can be seen petrographically and in the bulk chemistry variations within single units. At Site 395 there is substantial scatter in Al_2O_3 -contents, but the aggregate analyses exhibit crude plagioclase control. Clinopyroxene phenocrysts are also distributed sporadically and some sections lack clinopyroxene altogether. Unit B-396B shows a progressive change in composition from base to top towards a more evolved composition. This bulk chemical trend is matched by a less pronounced but parallel variation in the compositions of the residual glasses.

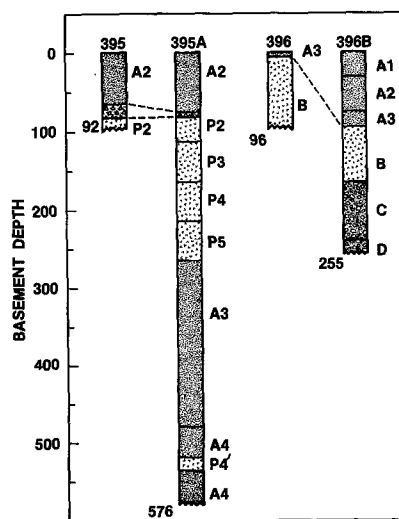


Fig. 1. Basalt stratigraphy at Sites 395 and 396—DSDP. Dense stipple indicates aphyric basalt. Open symbol indicates phyric basalt

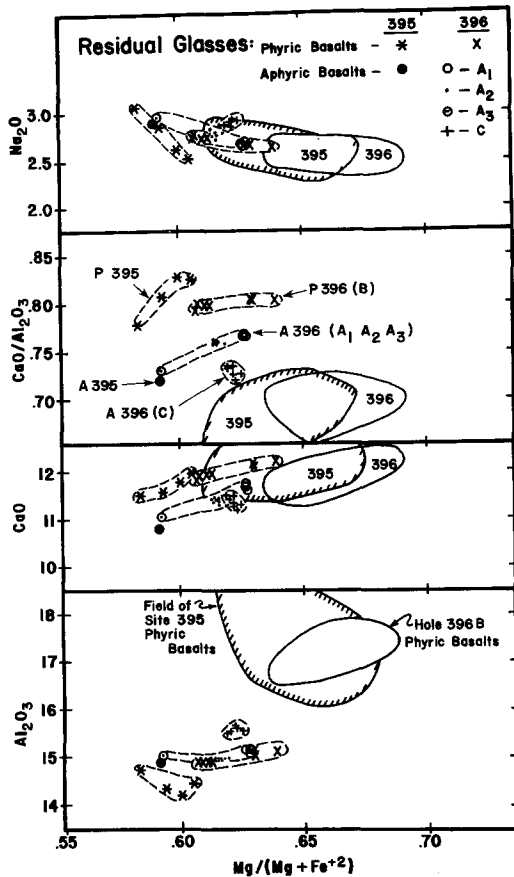


Fig. 2. Residual glass compositions in aphyric and phyric basalts and compositional fields for phyric basalts from both sites. Ordinate, weight percent; abscissa, atomic proportions

Residual Glasses

Compositional relationships among residual glasses and melt inclusions are shown in Figures 2, 3, and 4 where TiO_2 , $Mg/(Mg + Fe^{+2})$, CaO/Al_2O_3 , Na_2O , CaO and Al_2O_3 are plotted in different combinations. The compositional fields defined by the phyric basalts from Sites 395 and 396 are also shown for reference. The residual glasses are displaced from the bulk analyses of the phyric basalts in accordance with the presence of abundant plagioclase and olivine in the latter. The Site 395 basalts are somewhat more evolved than those at 396 but abundant overlap is present. Similarly the phyric glasses from the Site 395 basalts have lower $Mg/(Mg + Fe^{+2})$ than the Site 396 phyric glasses.

The purpose of this section is to examine the proposition that these basaltic liquids might be related by fractional crystallization, and if so, how. The elemental plots were chosen in order to isolate the effects of olivine, plagioclase and clinopyroxene removal in

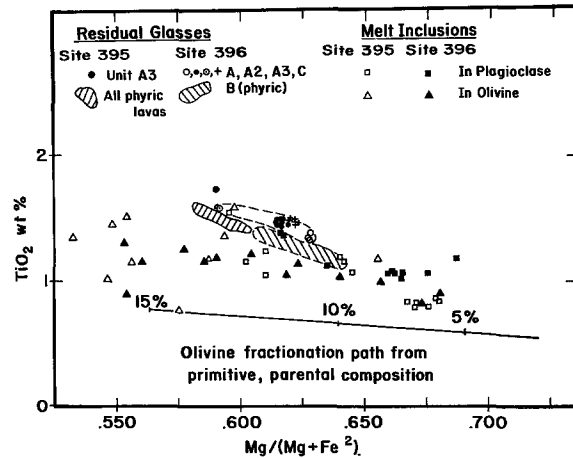


Fig. 3. Residual glasses and melt inclusions from both sites (weight percent). The olivine control line is based on olivine addition to the primitive liquid composition No. 4 in Table 4

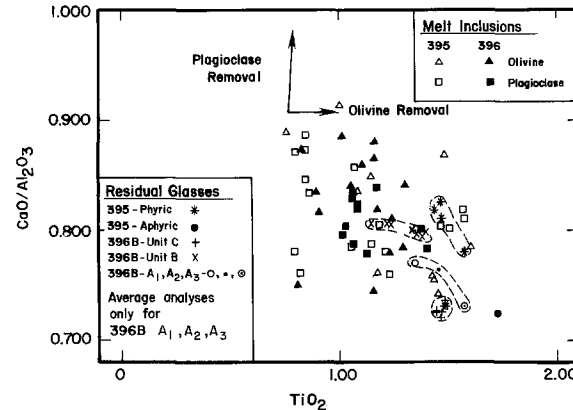


Fig. 4. Residual glasses and melt inclusions from both sites. Vectors indicate chemical changes with olivine and plagioclase fractionation

crystal fractionation processes. Titanium acts as a relatively magmaphile element (olivine or plagioclase $K_D = 0.01$ - Hekinian and Bougault, 1976). The ratio of $Mg/(Mg + Fe^{+2})$ is sensitive to olivine fractionation but remains constant during plagioclase fractionation whereas the CaO/Al_2O_3 ratio is similarly constant in response to olivine removal. Plagioclase ($CaO/Al_2O_3 \approx 0.5$) and clinopyroxene ($CaO/Al_2O_3 \approx 5$) change the calcium-aluminum ratio in opposite senses. Thus, a lowering of the calcium-aluminum ratio is the only definitive indication of clinopyroxene subtraction.

The following discussion is based primarily on data from glasses in Units A, B, and C-396B because the abundance of analyses from single units provides the best control and because clinopyroxene phenocrysts are absent. The fields of closely related residual glasses at individual sites are circumscribed by dashed

lines. The four identified fields are Unit B-396B, Unit C-396B, all phyrice glasses at Site 395 and the average analyses of Units A₁, A₂ and A₃-396B.

At each site there is some overlap in Mg/(Mg+Fe⁺²) between the residual glasses in phyrice basalts and the compositions of the aphyric basalts. The oxide variations that distinguish the aphyric glasses from the fundamentally similar phyrice glasses are the lower CaO and higher TiO₂ of the former. Derivation of the aphyric glasses from phyrice glasses by fractional crystallization of olivine and plagioclase is not feasible even for glass compositions as similar as these because this mechanism would require an increase in the CaO/Al₂O₃ ratio. The aphyric glasses have slightly higher Al₂O₃ and consequently, for each site, the aphyric glasses have lower CaO/Al₂O₃ at a given Mg/(Mg+Fe) than any glasses in phyrice basalts. The combination of lower CaO and CaO/Al₂O₃ ratio and the higher TiO₂ in the aphyric glasses is also the trend of progressive fractionation among related units. With increasing evolution, inferred from decreasing Mg/(Mg+Fe⁺²), the circumscribed fields all show decreasing CaO and CaO/Al₂O₃ and increasing TiO₂. This type of chemical variation is clearly anomalous with respect to the presence of only plagioclase and olivine phenocrysts in the 396B basalts. In a fractional crystallization scheme in which the most primitive Unit B (396) glass serves as a model parent for the progressively more evolved Site 396 aphyric basalts, the removal of clinopyroxene is implied by the chemical trends. The absence of clinopyroxene phenocrysts in these rocks, therefore, appears to preclude straightforward derivation of these basalts from each other or from a common parent by simple fractional crystallization.

Unit C (396B), the sparsely phyrice basalt unit, has trace element systematics quite distinct from A and B. Thus the possibility that C and A-B are derived from the same parental liquid is eliminated (Dungan et al., 1978b). Despite the trace element evidence for distinct parental liquids, the Unit C glass compositions are very similar to those in Unit A₂ in that they have the same Mg/(Mg+Fe⁺²), TiO₂, CaO and MgO. However, Unit C is characterized by higher Al₂O₃, Na₂O, K₂O, P₂O₅ and lower FeO, SiO₂, and CaO/Al₂O₃ (Table 2). Although the differences are quite small for most of these elements, there is no combination of reasonable phenocryst phases that can be subtracted from any of the more primitive Unit A or B glasses to produce the Unit C glasses.

Bryan (1978) noted that all the glasses analyzed in basalts from the FAMOUS area fall on a plagioclase-olivine cotectic in the *ol-pl-cpx* ternary, regardless of whether the rocks contain only olivine and spinel phenocrysts or olivine, plagioclase and clinopy-

Table 2. Representative analyses of residual glasses from Site 395 and Unit B-396-B

JSC No.	154	115	140	226	238	249
SiO ₂	50.44	50.69	50.65	50.52	50.78	50.69
TiO ₂	1.73	1.44	1.58	1.38	1.23	1.15
Al ₂ O ₃	14.93	14.23	14.75	14.90	15.05	15.16
Cr ₂ O ₃	0.03	0.04	0.04	0.05	0.05	0.05
FeO*	9.90	9.98	9.88	9.84	9.17	8.97
MnO	0.21	0.14	0.20	0.19	0.17	0.19
MgO	7.51	7.42	7.24	7.69	7.87	8.02
CaO	10.79	11.77	11.50	11.81	12.12	12.18
Na ₂ O	2.93	2.59	3.07	2.73	2.64	2.63
K ₂ O	0.15	0.11	0.12	0.12	0.11	0.11
P ₂ O ₅	—	—	—	0.12	0.10	0.10
Total	99.02	98.41	99.40	99.35	99.29	99.25
Mg'	0.591	0.600	0.583	0.607	0.630	0.639
CaO/Al ₂ O ₃	0.723	0.827	0.780	0.793	0.805	0.803
CaO/Na ₂ O	3.7	4.5	3.7	4.3	4.6	4.6

FeO* Total iron expressed as FeO: Mg' = mol. prop. Mg/(Mg+Fe⁺²) after adjusting Fe⁺³/Fe⁺² = 0.1

154: Aphyric Basalt Unit A₃-395A

115: Olivine-plagioclase-clinopyroxene phyrice basalt P₂-395

140: Olivine-plagioclase phyrice basalt P₃-395A

226, 238, 249: Olivine-plagioclase phyrice basalts from the top, middle and bottom of B-396B

roxene. Furthermore, despite varying proportions of phenocryst phases (particularly plagioclase) in the basalts, the amount of normative plagioclase in the residual glasses remains nearly constant. Although Melson et al. (1976) call attention to the departure of their total range of glass analyses from average MORB (as originally defined by Engel et al., 1965), the vast majority of these glasses are moderately evolved tholeiites that closely resemble the basalts at Sites 395-396.

Melt Inclusions

Petrography and Mode of Entrapment

The inclusions in olivine crystals generally occur as one or two per grain and have spherical or subspherical morphologies (Fig. 5a). As Watson (1976) notes, the tendency toward sphericity is probably due to equilibration between the melt and the host phase after incorporation. These inclusions were probably trapped during growth along non-planar interfaces, which are characteristic of olivine crystallization from a melt at high growth rates (Donaldson, 1976). Inclusions in plagioclase are of at least two types. Small (1-15 μm) and abundant inclusions, such as those figured by Watson (1976), that occur in concentrations

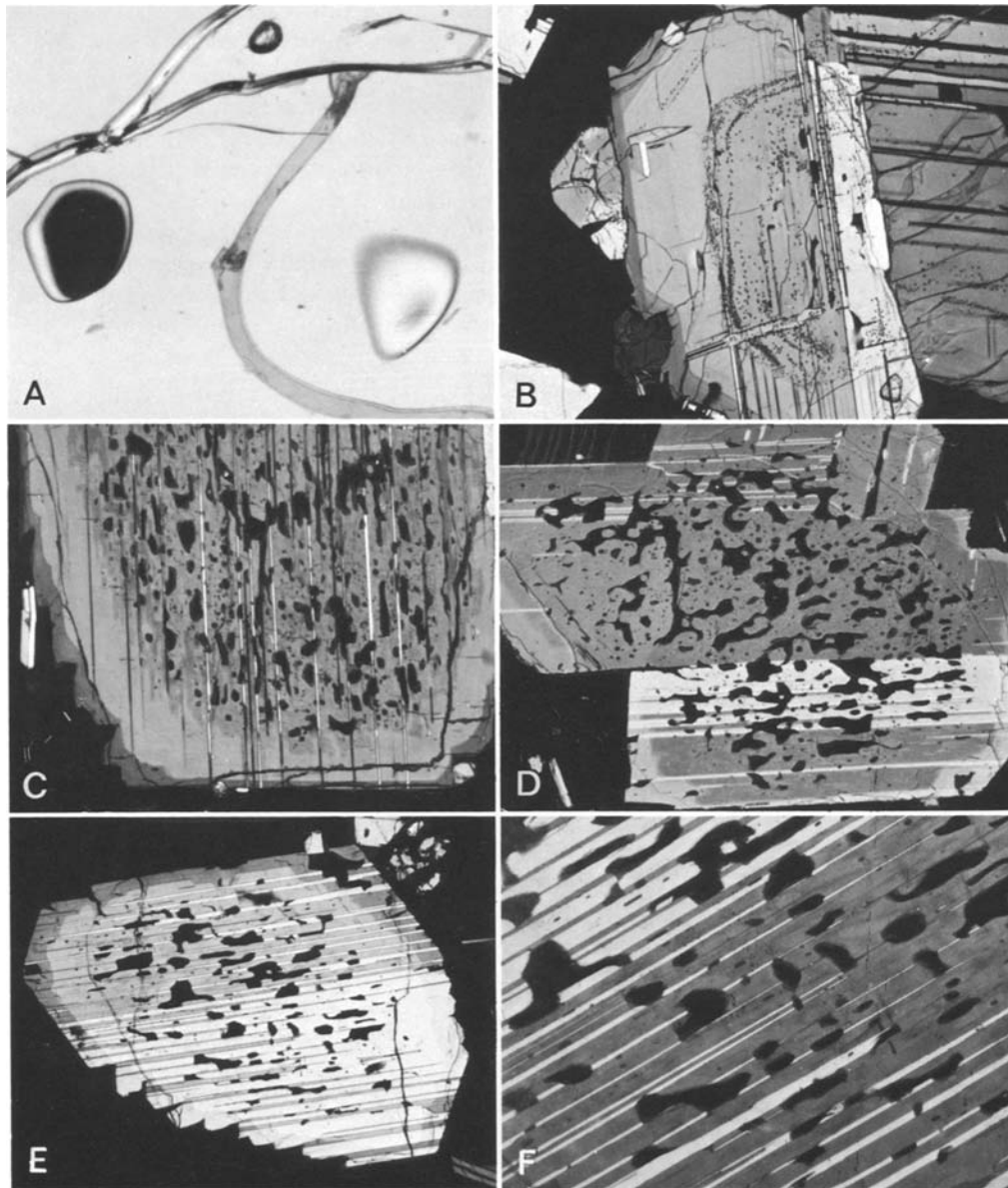


Fig. 5A-F. Photomicrographs of melt inclusions in olivine and plagioclase phenocrysts. **(A)** Two subspherical inclusions in a large olivine phenocryst – width of field = 0.25 mm. **(B)** Plagioclase glomerocrystic aggregate containing small melt inclusions trapped during primary growth – width = 3 mm. **(C)** Irregular melt inclusions in a complexly corroded plagioclase phenocryst (JSC No. = 115). The inclusion-rich core composition is An_{78-75} . Very narrow calcic rims (An_{80}) occur around some melt inclusions. The light gray intermediate rim is An_{85} and is in turn mantled by an outer rim of An_{74-69} – width = 1.2 mm. **(D)** Another plagioclase glomerocryst containing abundant irregular melt inclusions. Note how some of the inclusions cut grain boundaries formed by synneusis twinning – width = 2.5 mm. **(E), (F)** Melt inclusion-rich phenocryst and detail of same showing melt inclusions bonded by polysynthetic twin lamellae – widths of fields = 2.5 mm and 0.8 mm

parallel to growth surfaces in plagioclase crystals are clearly the result of entrapment during original growth of the crystals (Fig. 5b). Very few of these have been analyzed in this study because of their small size.

A second type consisting of irregular shaped melt inclusions has been emphasized in microprobe analysis. These were originally chosen because of their

larger size, but it was subsequently recognized that they are melts entrapped in plagioclase phenocrysts as the result of extensive resorption of these phenocrysts. Petrographic criteria for the recognition of such melt inclusions are discussed in detail below because melt inclusions of irregular morphology may also be trapped in plagioclase phenocrysts during rapid primary growth.

The irregular melt inclusions typically occur in large plagioclase cores that are mantled by inclusion-free rims. The boundary between core and rim exhibits two features that support the corrosion hypothesis. There is generally a compositional discontinuity between the core and the mantle. The hiatus can be as large as 10 mol%. An and is present between both calcic core-sodic rim and sodic core-calcic rim pairs (Fig. 5c and d). In the case of a melt inclusion-rich core surrounded by a more calcic rim, the boundary is generally highly irregular and is apparently corroded (Fig. 5c and d). In these instances the melt inclusions are markedly different in composition from the residual glasses in being more primitive (i.e., high $Mg/(Mg + Fe^{+2})$, low TiO_2) and are typically rimmed by thin marginal zones more calcic than the core plagioclase.

In contrast to the concentric distribution of smaller melt inclusions trapped during primary growth, the grid-like pattern of the irregular shaped melt inclusions suggest melting controlled by intersecting cleavage planes or possibly by pre-existing melt inclusions. Another important characteristic is that the melt inclusions tend to be bounded by polysynthetic albite twin planes and are preferentially elongate parallel to them. As polysynthetic twinning is known to postdate crystal growth, the melt inclusions must, therefore, also be produced after the crystals were fully formed. An example of this type of occurrence is shown in Figure 5e and f. These inclusions also cross planar grain boundaries in glomerocrystic aggregates formed by synnesis (Vance, 1969).

On the basis of this petrographic evidence we infer that melt inclusions in plagioclase of the second type were trapped after an episode of corrosion of plagioclase phenocrysts brought on by disequilibrium with the enclosing liquid. This disequilibrium could have been the result of: (1) the immersion of the plagioclase phenocrysts in liquids with different compositions than those in which they grew or (2) a precipitous change in a physical parameter, such as vapor composition, that could produce a change in the equilibrium plagioclase composition. We regard the second hypothesis as highly unlikely in light of the evidence for the very low vapor contents of MORB (Delaney and Meunow, 1976).

The significance of the secondary melt inclusions is that they appear to be remnants of three dimensional, interconnecting channel systems that were filled with melt in communication with the surrounding liquids. This inference is based on textural evidence for resorption, the relatively large volume of liquid trapped in some crystals compared to growth-trapped melt inclusions and microprobe analyses indicating that these melt inclusions are nearly of a single

composition. Individual melt inclusions trapped during the growth of single olivine phenocrysts are always distinctly different in chemistry. Consequently we interpret the secondary melt inclusions in plagioclase as having formed by entrapment of matrix liquid present at the time of resorption. Subsequent to corrosion and entrapment, these melt inclusions become isolated from the host melt by the precipitation of an overgrowth of new plagioclase. One example of a plagioclase phenocryst in a Site 396 phyric basalt, that was not mantled by a post-resorption overgrowth, contains melt inclusions virtually identical to the enclosing residual glass (Tables 3: analyses 4 and 5).

Melt Inclusion Chemistry

Relative to the residual glasses, the melt inclusions trapped within olivine and plagioclase phenocrysts exhibit substantial compositional variation. Part of the diversity and deviation from residual glass compositions is due to crystallization of the host phase from the trapped melt. This effect is more pronounced in those included in olivine than in plagioclase. Similarly, melt inclusions trapped during resorption may be contaminated by melted host phase. The anomalously high silica-contents of some secondary melt inclusions may be due to plagioclase contamination. A third reason for the wide range of compositions is that the melt inclusions represent entrapment of residual liquids of varying chemistry. This is illustrated in Figure 3 by the wide range of TiO_2 -contents present in melt inclusions in olivine phenocrysts from both sites. An example of the effect of olivine fractionation from a primitive basaltic liquid shows that the total TiO_2 variation in the inclusions is several times greater than the amount that can be accounted for by olivine fractionation from a single parental liquid. Note that several of the melt inclusions (in both plagioclase and olivine) have TiO_2 -contents less than 1.0 wt% and that values of 0.8 wt% TiO_2 are not uncommon (Table 3). Similarly, many of the melt inclusions have CaO/Al_2O_3 greater than 0.83, which is the maximum value for the residual glasses. This feature is further illustrated in Figure 4. Note that there is a broad correlation between decreasing CaO/Al_2O_3 and increasing TiO_2 among the melt inclusions. The large amount of scatter in these data is a reflection of post-entrapment modification of somewhat diverse liquids. Of prime importance, however, are the few olivine melt inclusions with very high CaO/Al_2O_3 and low TiO_2 . These inclusions occur in magnesian olivine phenocrysts and are potentially primitive liquids.

Table 3. Selected Microprobe Analyses of Glass Melt Inclusions in Olivine and Plagioclase Phenocrysts

	1	2	3	4	5	6	7	8	9
JSC No.	115.1	115.8	239.7	236.4	236	45G.1	238.1	237.1	249.1
SiO ₂	49.61	52.24	50.72	50.57	50.72	51.22	51.00	51.79	50.81
TiO ₂	0.86	0.80	1.02	1.38	1.40	0.77	0.90	0.84	0.91
Al ₂ O ₃	14.28	13.88	15.58	14.93	14.99	16.98	17.78	14.16	16.30
Cr ₂ O ₃	0.06	0.05	0.06	0.04	0.05	0.07	0.05	0.06	0.06
FeO*	9.39	8.61	8.72	9.63	9.64	7.80	7.88	8.45	7.49
MnO	0.13	0.16	0.16	0.17	0.18	0.15	0.17	0.13	0.15
MgO	10.00	8.79	8.67	7.82	7.72	5.33	4.94	8.80	7.96
CaO	11.89	12.18	12.38	11.91	11.94	15.11	14.90	12.37	13.33
Na ₂ O	2.21	2.36	2.56	2.70	2.74	2.00	2.35	2.36	2.42
K ₂ O	0.07	0.09	0.12	0.12	0.11	0.04	0.06	0.08	0.10
Total	98.50	99.16	99.99	99.27	99.42	99.47	100.03	99.04	99.53
Mg/(Mg+Fe ⁺²)	0.678	0.669	0.663	0.617	0.613	0.575	0.554	0.673	0.680
CaO/Al ₂ O ₃	0.832	0.878	0.795	0.798	0.796	0.890	0.838	0.874	0.817
Phase	Plag.	Plag.	Plag.	Plag.	Resid.	Oliv.	Oliv.	Oliv.	Oliv.

JSC No. refers to Table 5 in Dungan et al. (1978b)

115: Olivine-plagioclase-clinopyroxene phyric basalt (P2-395). Melt inclusions occur in the cores of resorbed plagioclase phenocrysts (An₇₅₋₇₈). Both grains have inclusion-free rims of more calcic (An₈₅) plagioclase overgrown on the inclusion-rich core

239.7: A similar occurrence in an olivine-plagioclase phyric basalt (B-396B)

236.4, 236: A melt inclusion in a corroded plagioclase phenocryst compared to matrix residual glass. No overgrowth of post-resorption plagioclase is present (B-396B)

45G1, 238.1, 237.1, 249.1: Olivine melt inclusions with low TiO₂ that were trapped during growth (P2-395 and B-396B)

Derivation of Primitive Liquid Compositions From Melt Inclusions

Anderson (1974), Watson (1976), and Donaldson and Brown (1977) have emphasized the usefulness of melt inclusions in identifying primitive liquids that are potentially parental to the more evolved basalts in which the enclosing phenocrysts occur. The discussion which follows is based in part on assumptions regarding the use of melt inclusions that have been given in Anderson (1974 and 1976). The Site 395-396 phyric basalts contain abundant large phenocrysts of olivine that are too magnesian (Fo₈₉₋₉₀) to be in equilibrium with liquids of the host composition (Dungan et al., 1978b). Such phenocrysts are, however, appropriate for more primitive basalts with Mg/(Mg+Fe⁺²) = 0.70-0.72. Rhodes and Dungan (1977) have proposed that presently available compositional and experimental data indicate that an identifiable and restricted liquid composition is not only a common parental magma for ocean floor basalts, but is probably derived directly from partial melting of the mantle. Three representative examples of primitive magma compositions are listed in Table 4 (1-3).

In addition to their high Mg/(Mg+Fe⁺²) these primitive magmas are characterized by low TiO₂

(0.6-0.8 wt% TiO₂), high CaO/Al₂O₃ (>0.75) and high CaO/Na₂O (>6.0) (see also Byerly and Wright, 1978). There is a clear convergence on these four criteria by the melt inclusions analyzed in this study. Melt inclusions in olivines with low TiO₂-contents are also characterized by high CaO/Al₂O₃; and low-TiO₂ inclusions in plagioclase phenocrysts have high Mg/(Mg+Fe⁺²) relative to the associated residual glasses and host basalt compositions.

The melt inclusions trapped in olivine, plagioclase and clinopyroxene phenocrysts in a South Atlantic porphyritic tholeiite analyzed by Watson (1976) show the same convergence on these chemical characteristics, and the recalculated melt compositions exhibit a distinct affinity to those in Table 4. However, the graphical method of back-calculation, which relies on extrapolations from melt compositions trapped in all three phenocrysts phases, results in a factor of two variation in TiO₂ which belies Watson's assertion that there is an absolute convergence on a singular composition. His assumption that olivine, plagioclase and clinopyroxene simultaneously trapped a unique back-calculated composition is in contradiction to the implication that this melt was sufficiently evolved to be triply saturated. If this melt were both primitive and multiply saturated it would be in sharp

Table 4. Possible Parental Magmas for Ocean Floor Basalts

	1	2	3	4
SiO ₂	50.3	49.4	48.96	49.58
TiO ₂	0.73	0.81	0.82	0.65
Al ₂ O ₃	16.6	15.64	15.75	14.43
FeO	7.99	7.44	8.52	8.19
MnO	0.12	0.15	0.13	—
MgO	10.2	10.01	9.79	11.64
CaO	13.2	12.93	11.92	12.89
Na ₂ O	2.00	1.95	1.97	1.70
K ₂ O	0.01	0.17	0.11	0.03
P ₂ O ₅	n.d.	0.08	n.d.	0.04
S	n.d.	0.06	n.d.	n.d.
Cr ₂ O ₃	0.07	0.14	n.d.	n.d.
Total	101.22	98.78	97.97	99.14
Mg/(Mg+Fe ⁺²)	0.717	0.727	0.695	0.717
CaO/Al ₂ O ₃	0.795	0.827	0.757	0.893
CaO/Na ₂ O	6.6	6.6	6.1	7.6

1: Frey, et al. (1974) South Atlantic

2: Rhodes—45° N MAR

3: Bryan and Moore (1977) FAMOUS No. 525-5-3

4: Reconstructed composition of melt inclusion 45G1 (Table 3) such that Mg/(Mg+Fe⁺²) ≈ 0.72

contrast to the occurrences of only olivine and chromian spinel phenocrysts in examples of primitive ocean floor basalts such as those in Table 5, which it closely resembles chemically.

We have attempted to calculate the most primitive trapped liquid by choosing for a starting composition the olivine melt inclusion that has both very low TiO₂ and very high CaO/Al₂O₃ (Fig. 5a—Table 3, column 6). The method of calculation was to subtract 12% olivine of the appropriate composition (Fo₈₄, Fo₈₈, Fo₈₉) in small increments so that the olivine was in equilibrium with the liquid. The resulting composition, listed in Table 4 (No. 4), was arrived at by adjusting the final Mg/(Mg+Fe⁺²) to 0.72. This value was chosen to correspond to the liquid in equilibrium with the olivine phenocryst in which it occurs (Fo_{89.5}). Although this particular melt inclusion has undergone substantial fractionation by crystallization of the host olivine, the most magnesian melt inclusions in plagioclase phenocrysts have Mg/(Mg+Fe⁺²) of 0.68–0.69. Thus, the extrapolation to 0.72 is not only reasonable in terms of the magnesian olivine phenocrysts but it only slightly exceeds the natural maximum. Furthermore, the calculated equilibrium plagioclase composition (at 1250° C) for the calculated parental liquid is An₈₄, which is consistent with the An_{86–83} phenocrysts in the phyric basalts.

The similarities between the liquid calculated from the melt inclusion and the three primitive basalts

listed in Table 4 are striking. We suggest that this calculated composition is representative of the parental liquid from which the Site 395 and 396 basalts were derived. However, there is not a continuum between this potential parent and the most primitive phyric basalts at the two sites (i.e., TiO₂=0.9–1.0, Mg/(Mg+Fe⁺²)=0.685 for the basalts). The inferred parental liquid lies well outside the range of compositions defined by the residual glasses and the most primitive phyric basalts.

Anderson and Wright (1972) and Anderson (1976) have found that the adjusted compositions of some melt inclusions in phenocrysts of certain Kilauean and calc-alkaline lavas are more evolved than the matrix residual glasses. Anderson (1976) argues that this relationship is *prima facie* evidence for magma mixing because these melts lie outside the range of chemical variation defined by the bulk rock compositions and because the residual glasses and the inclusions do not contain additional daughter minerals. In the case of a trapped liquid which is more primitive than the bulk compositions, magma mixing is probably not proven although we believe it is strongly indicated. The alternative, which is favored by Watson (1976), is that early formed crystallization products of a very primitive liquid remain suspended during further fractionation and are ultimately erupted in moderately evolved lavas. However, this occurrence is puzzling because of the presence of relatively primitive liquids in three phenocryst phases. If Watson's interpretation is correct, it represents an unusual example of a triply saturated liquid derived directly from partial melting of the mantle. An alternative explanation which we favor is that relatively unfractionated basalts carrying melt inclusion-bearing olivine phenocrysts are injected into subvolcanic magma chambers beneath mid-ocean ridges, where they become intermingled with evolved liquids and associated phenocrysts. Some of the plagioclase phenocrysts that have formed in fractionated magmas will become resorbed in response to disequilibrium resulting from immersion in the new composition. The melt inclusions trapped in these corroded phenocrysts will be representative of a hybrid liquid generated by the mixing process.

We have noted previously (Rhodes et al., 1978b) that the extensive disequilibrium between olivine and plagioclase phenocrysts and their host liquids in the phyric basalts is evidence of hybridization in these rocks. The preponderance of phenocrysts that are either too forsteritic or anorthitic suggests a large contribution to the phyric basalts by crystal-rich primitive basalts. The primitive melt inclusions trapped in these phenocrysts are further evidence for the participation of a primitive end-member liquid.

The Site 395–396 phyric basalts are very plagioclase-rich and have plagioclase on the liquidus in one-atmosphere melting experiments. On the other hand, primitive ocean floor basalts listed in Table 4 are all olivine phyric. The derivation of moderately evolved plagioclase tholeiites from primitive olivine tholeiite by low-pressure fractionation is in contradiction to the well established presence of an olivine-plagioclase cotectic in ocean floor basalts (Shido et al., 1971; Bryan, 1978). We suggest that so-called plagioclase tholeiites are merely an artifact of mixing evolved with primitive basalts plus a zone of plagioclase accumulation within magma chamber.

Thus, the phyric basalts not only provide abundant evidence that magma mixing is important in the petrogenesis of ocean floor basalt but the primitive melt inclusions and phenocrysts constrain the composition of one of the end member components of the mixing process. Establishing the composition of the evolved end-member is more difficult. The scarcity of reversely zoned phenocrysts in phyric basalts indicates that it tends to be very sparsely phyric. In the following section we discuss additional petrologic implications of this mixing model and how constraints on the process of mixing coupled with fractional crystallization have been derived.

Implications of Magma Mixing for Geochemical Modeling of MORB Differentiation

The combined melt inclusion and residual glass data provide a powerful constraint against a closed system-single batch fractionation scheme involving the primitive basalt composition and olivine and plagioclase phenocrysts. *The key evidence is the paradox of decreasing $\text{CaO}/\text{Al}_2\text{O}_3$ in residual glasses with increasing crystallization of olivine and plagioclase.* The anomaly in the trends defined by the aphyric and phyric glasses is further accentuated by the even higher $\text{CaO}/\text{Al}_2\text{O}_3$ and lower TiO_2 of the primitive melt inclusions in olivines. Any model that explains the decrease in calcium-aluminum ratio with progressive fractionation must resolve the contradiction posed by the absence of clinopyroxene in the majority of the Site 395 basalts and all the Site 396 basalts.

The chemical anomaly embodied in these glass data is representative of a two-fold problem that has been encountered repeatedly in geochemical modeling of ocean floor basalt fractionation. Most of the previous studies depended on computer modeling techniques (e.g., Bryan et al., 1969; Wright and Doherty, 1970) to relate apparently consanguineous deep sea basalts recovered by drilling, dredging or submersibles (Clague and Bunch, 1976; Herkinian et al., 1976; Bryan

et al., 1976; Bryan and Moore, 1977; Byerly and Wright, 1978). Although the results of these calculations confirm that fractional crystallization of the phenocryst phases olivine, plagioclase and clinopyroxene does indeed play an important role in controlling ocean floor basalt chemistry, the following two discrepancies frequently emerge in these studies. The first is that, in order to obtain mathematically reasonable solutions, the calculated proportion of clinopyroxene in the fractionating mineral assemblage is invariably too high to be compatible with its observed modal abundance. Secondly, the concentrations of elements such as Ti, REE, Y, and Zr have been found to be anomalously high in the evolved daughter compositions relative to values calculated from the fractionation of a reasonable parent liquid. Our analysis of chemical relationships in the Leg 45 and 46 basalts indicates that these two anomalies are manifestations of combined fractionation and magma mixing. They are discussed below.

Magma Mixing and the "Clinopyroxene Paradox"

Melting experiments on the Leg 45–46 basalts (Dungan et al., 1978a and b) demonstrate that clinopyroxene follows olivine, spinel and plagioclase in the crystallization sequence by 50–80° C. This is a general observation that holds equally well for both plagioclase and olivine tholeiites (Miyashiro et al., 1969; Shido et al., 1971). However, this relationship does not in itself explain the dichotomy of the chemical imprint of clinopyroxene fractionation in the absence of phenocrysts. Periodic replenishment of the subvolcanic magma chamber will tend to keep the resultant hybrid liquids crystallizing only plagioclase and olivine. Mixing of primitive basalt with cotectic liquids perturbs the system chemically and thermally, moving the liquids away from pyroxene saturation. Because the mixing of magmas is likely to trigger convective overturn within the chamber, chemical and thermal gradients will be lessened. As the chamber cools and crystallization recommences following the mixing event, the largest heat loss will be to the upper walls. Consequently, it is on these walls that the precipitation of clinopyroxene will first occur. We suggest that MOR magma chambers evolve in part by plating of clinopyroxene and plagioclase onto the chamber walls or roof in a manner analogous to the marginal and upper Border Groups of the Skaergaard intrusion (Wager and Brown, 1967). The subsequent convective circulation of these relatively cool, clinopyroxene-depleted magmas with hotter olivine-plagioclase magmas in the central region of the chamber accounts for the clinopyroxene paradox. This scenario not only

provides a mechanism to generate evolved magmas with low $\text{CaO}/\text{Al}_2\text{O}_3$ and no clinopyroxene phenocrysts, but it also allows for effective segregation of differentiated liquids from their refractory crystalline residues. The latter is clearly a requirement for the eruption of the ubiquitous and voluminous aphyric basalts of the ocean floor.

Recent physical models of spreading ridge evolution proposed by Jackson et al. (1975), Sleep (1975), and Dewey and Kidd (1977) are built around the assumption of continuous replenishment of the subvolcanic magma chamber of substantial size and infer a major role for crystallization of plagioclase and clinopyroxene on the magma chamber roof. The field observation of rootless diabase dikes in non-cumulus gabbro that extend upward into overlying sheeted dike complexes in Newfoundland ophiolites is a particularly compelling indication that this process occurs (Dewey and Kidd, 1977).

Hopson et al. (1977) have also found evidence for repeated influx of fresh, primitive magma in the ultramafic cumulates and layered gabbros of the Semail ophiolite in Oman. At the base of the cumulate sequence there are numerous cycles of olivine-plagioclase-clinopyroxene cumulates, each of which begins with olivine precipitation. Overlying this basal zone is a large thickness of gabbro characterized by an upward decrease in modal olivine. The mineral chemistry variations in this gabbroic section exhibit far less progressive fractionation than in the Skaergaard intrusion. Thus the cumulus mineralogy of these gabbros records the periodic retardation of fractionation resulting from magma replenishment.

The presence of cumulus clinopyroxene in most ophiolite sequences and some gabbros dredged from the ocean floor indicates that some of the fractionation does take place by settling of phenocrysts. Hodges and Papike (1976) have argued that clinopyroxene in some gabbros recovered in Hole 334 (DSDP) crystallized as an intercumulus phase from liquid still in diffusional contact with the overlying liquid. Thus the plating-on mechanism we propose is probably not the only process contributing to clinopyroxene fractionation in the midocean ridge setting.

Magma Mixing and the "Magmaphile Element Excess"

In the previous section we have demonstrated the existence of cryptic clinopyroxene fractionation in the Leg 45–46 basalts. Because of the way that this chemical imprint is imparted to the liquids, the differentiation cannot be modeled solely in terms of fractional

crystallization. The exaggerated amount of clinopyroxene removal that is calculated in least-squares modeling of chemical relationships among apparently consanguineous MORB (cf. Clague and Bunch, 1976) is in part a reflection of the fractionation mechanism described above.

Another factor in the failure of this approach to successful modeling of MORB differentiation may be a consequence of the mathematics involved. The abundances of incompatible elements will increase logarithmically with increasing fractionation and will tend to be in excess of the amounts calculated from a linear mixing model. However, it is the same logarithmic magmaphile element increase that actually does generate a real excess of these elements in MORB.

Following O'Hara (1977) we have attempted to relate the anomalous excess of magmaphile elements to magma mixing. Our approach to this problem is presented in detail in Rhodes et al. (1978b) and will only be summarized here. We have combined Rayleigh fractionation calculations and least-squares calculations to derive estimates of the discrepancy between simple fractional crystallization models and a more complex scheme in which magma mixing is involved.

The crux of this analysis is that liquids which fall on a mixing line between an unfractionated primitive magma and one that is highly evolved will have substantially higher concentrations of magmaphile elements than are predicted by Rayleigh fractionation, which is a boundary condition for incompatible element behavior in fractionating basalts. Mixing of a primitive, unfractionated magma, such as those listed in Table 5, with a liquid that is 75% fractionated by removal of olivine, plagioclase and clinopyroxene gives a mixing line solution that satisfies the Leg 45–46 data in terms of percent solidified (≈ 35 – 45 for aphyric lavas as calculated by least-squares modeling). The magmaphile elements are enriched by a factor of 2 ± 0.2 as compared to the 1.5x enrichment predicted by Rayleigh fractionation. Least squares modeling of the Leg 45–46 basalts gave solutions for the fractionating assemblage in which clinopyroxene constituted over 50% of the material subtracted. This overdependence on clinopyroxene fractionation is an attempt to generate a reasonable *mathematical* solution in response to the magmaphile element excess. This results because clinopyroxene fractionation provides a mechanism for increasing the amount of crystalline material that has been removed while simultaneously buffering the major element composition of the magma.

Although a one-stage mixing model illustrates the fundamental relationships, a more probable mechanism is incremental enrichment of magmaphile ele-

ments by repeated episodes of mixing of relatively primitive and moderately evolved magmas. If each mixing event is followed by a small amount of fractionation, the concentrations of magmaphile elements will gradually increase but the major element composition of the magma will remain essentially constant (O'Hara, 1977).

Conclusions

We have shown that microprobe analyses of natural glasses in Leg 45–46 ocean floor basalts, interpreted in the context of other geochemical, petrographic and experimental data on the same rocks (Rhodes et al., 1978 b), are useful in establishing constraints on their differentiation history. Primitive liquids entrapped in early olivine phenocrysts provide an indication of the composition of the magma parental to the observed evolved basalts. After back-calculation to remove the chemical effects of host-phase crystallization, the distinct chemical characteristics of this primitive magma are high $Mg/(Mg + Fe^{+2})$, CaO/Al_2O_3 , CaO/Na_2O and low lithophile element concentrations as typified by $TiO_2 < 0.8$ wt%. Olivine melt inclusions with higher TiO_2 and lower CaO/Al_2O_3 record entrapment of more fractionated liquids, ranging up to the most evolved liquids we observe, the residual glasses. That this calculated parental liquid is indeed a primitive mantle-derived melt is supported by the presence of other basalts recovered from the Atlantic with very similar chemistry which fulfill criteria for unfractionated liquids (Rhodes and Dungan, 1977).

A very important characteristic of the chemistry of the more evolved liquids in the Leg 45 and 46 glass collection is the progressive decrease in CaO/Al_2O_3 with increasing differentiation. This trend, recorded in both residual glasses and melt inclusions, demands clinopyroxene fractionation if the identified primitive liquid is parental to all the observed magmas. The paradox of progressive lowering of the calcium-aluminum ratio despite the total absence of clinopyroxene phenocrysts is interpreted as an indication of the importance of crystallization of "static" gabbros formed by plating of plagioclase and clinopyroxene onto the upper walls of the presumed subvolcanic magma chamber. This type of crystallization is consistent with current thermal models of mid-ocean ridges (Sleep, 1975) and the phase relations of ocean floor basalts which indicate that clinopyroxene is a near-solidus phase. This process is particularly plausible if, as we suggest, the magma chamber is periodically recharged by the influx of high-temperature, primitive magmas. The effect of this replenish-

ment will be to generate a hybrid, moderately evolved magma that will be displaced from triple saturation.

Many plagioclase phenocrysts in the Leg 45 and 46 basalts exhibit evidence of resorption at some point in their crystallization history. Most of these crystals consist of cores rich in irregular shaped melt inclusions. The cores are, in turn, rimmed by inclusion free overgrowths. Significantly this outer mantle may be either more or less calcic than the core. These melt inclusions are presumed to be recorders of matrix liquid at the time of extensive resorption of the host crystals. On the basis of abundant petrographic criteria, mineral chemistry data and one atmosphere experimental studies, the crystal-liquid disequilibrium responsible for the resorption is inferred to be the result of immersion of these plagioclase phenocrysts in liquids either more primitive or evolved than those from which they grew.

Plagioclase phenocrysts with inclusion-rich cores rimmed by more calcic, inclusion-free mantles contain melt inclusions that are relatively primitive compared to the bulk rock analyses of the phyric basalts; i.e., higher $Mg/(Mg + Fe^{+2})$ and lower TiO_2 . However, they are never as primitive as the inferred parental liquid. They probably represent liquids generated by an influx of primitive magma, mixing with more evolved liquid at the base of a chamber where crystals are accumulating. Their relatively unevolved chemical nature reflects a large component of the primitive magma.

Compilations of ocean floor basalt analyses (Hart, 1976; Melson et al., 1976) indicate that the vast majority of ocean floor basalts are moderately evolved tholeiites with cotectic mineralogy. Examples of primitive, picritic basalts and highly evolved FeTi-rich basalts are much less abundant and silicic differentiates are extremely rare. Thus, the remarkably constant composition of "typical MORB" (O'Hara, 1968) can be viewed as a buffered composition; i.e., there is something fundamental about basalt differentiation beneath mid-ocean ridges that prevents fractionation from proceeding unchecked. We suggest that, beneath mid-ocean ridges, the subvolcanic plumbing system rarely solidifies completely between episodes of magma generation and ascent and, therefore, acts as a trap for new magma batches as they arrive from depth. These unfractionated magmas are then inevitably mixed with fractionated magmas and possibly with zones of crystal accumulation. The resultant hybridized magmas are subsequently erupted with or without additional fractionation. Thus we envision the mixing process operating as a physical buffer dependent on a volume balance between relatively frequent eruptions and replenishment events.

The occurrence of the two petrographically distinct basalt types (aphyric and phyric) at the Leg 45

and 46 sites and elsewhere on the ocean floor may be a function of the timing of eruptive events relative to mixing events. The aphyric basalts appear to represent eruptions during periods of quiescence, with the mechanism of eruption being tensional fracturing unrelated to magmatic processes. The compositions of evolved aphyric lavas will vary according to the amount of time (=fractionation) elapsed since the previous episode of mixing. In contrast, the phyric basalts are recorders of actual mixing events in which the eruptions are triggered by the volume increase associated with the addition of a new batch of magma. The role of plate divergence in maintaining a magma chamber of roughly constant dimensions and the high magma production rates associated with mid-ocean ridge volcanism combine to make magma mixing a process with a very high probability of occurring in this tectonic setting. Indeed, any basaltic volcanic system in which magma production rates are high is likely to be characterized by moderately evolved tholeiites which have experienced at least some hybridization (cf., Wright and Fiske, 1971).

The magma mixing model for mid-ocean ridge volcanism, developed in Rhodes et al. (1978b) and expanded in this paper, accounts for many previously enigmatic geochemical and mineralogical characteristics of MORB. They are:

1. The abundance of moderately evolved cotectic tholeiites and the relative scarcity of highly evolved lavas and primitive basalts.

2. The chemical imprint of clinopyroxene fractionation and the apparent absence of clinopyroxene phenocrysts.

3. Anomalies encountered in the computer modeling of fractional crystallization of ocean floor basalts such as an excess of incompatible elements in evolved derivatives and the calculated over-participation of clinopyroxene in the fractionating assemblage.

4. The problematic occurrences of so-called plagioclase tholeiites (i.e., lavas rich in plagioclase phenocrysts with plagioclase on the 1-atmosphere liquidus) can be accounted for by mixing of zones of plagioclase accumulation with cotectic liquids.

The conclusions reached on the basis of geochemical and petrologic studies of the Leg 45–46 basalts are entirely consistent with observations of the plutonic portions of ophiolite complexes.

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