Composition and depth of origin of primary mid-ocean ridge basalts

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Abstract. Some workers have held that mid-ocean ridge basalts are fractionated from high pressure (15–30 kbar) picritic primary magmas whereas others have favored primary magmas generated at about 10 kbar with compositions close to those of mid-ocean ridge basalts. Of critical significance are presumed differences in composition between experimentally determined primary magmas and the least fractionated mid-ocean ridge basalts. To evaluate the significance of these differences, all based on electron microprobe analyses, we consider three sources of uncertainty: (1) analytical uncertainties for a single microprobe laboratory, (2) systematic interlaboratory analytical differences, and (3) real variations in the possible compositions of primary magmas that can be produced from a peridotite source at a given pressure. The first source of error is surprisingly large and can account for a substantial part of the total variation of normative quartz (hypersthene calculated as equivalent olivine and quartz) in FAMOUS basalts. The second is not as serious but remains undetermined for many laboratories. The third is potentially the largest but is not yet fully documented. The least fractionated FA-MOUS basalts have high *mg* numbers (70–73) compatible with derivation from the mantle by direct partial melting with little or no subsequent fractional crystallization. Because of the wide range of normative quartz content in these basalts, it appears necessary to consider them as representatives of multiple parental magmas. When all the sources of uncertainty are taken into account, we conclude that the experimental data by various investigators are all fairly consistent and favor derivation of the least fractionated mid-ocean ridge basalts by at most only a small amount of fractional crystallization from primary magmas having a wide range of normative quartz content and generated over a range of pressures from about 7–11 kbar.

Introduction

Basaltic magma has long occupied a central position in the development of petrogenetic theory, and classically was recognized as a primary magma derived by direct partial

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melting from the mantle. O'Hara (1965, 1968a, 1968b) challenged this well-established idea and argued that basalts as we see them on the earth's surface are not primary but are themselves the result of fractional crystallization from more primitive parents. For many basalts, he considered the parent to be a picritic magma generated at high pressures around 30 kbar.

Since 1965, the controversy over the primary or non-primary nature of various basalts has raged, and is currently represented in its most virulent form by disagreements over the origin of mid-ocean ridge basalts. Two opposing viewpoints have been vigorously advocated. O'Hara (1968), Green et al. (1979), Jacques and Green (1980), Stolper (1980), and Elthon and Scarfe (1980, 1984) have argued that the primary magmas are picritic, are produced at pressures ranging from 15 to 30 kbar (depending on the author), and yield the least fractionated of the mid-ocean ridge basalt (MORB) compositions by extensive crystallization of olivine. In contrast, Green and Ringwood (1967), Kushiro (1973), Presnall et al. (1979), Fujii and Bougault (1983), and Takahashi and Kushiro (1983) have argued that the compositions of the primary magmas are close to those of the least fractionated mid-ocean ridge basalts erupted at the surface and that these primary magmas are generated at pressures of about 8–10 kbar. All investigators agree that most mid-ocean ridge basalts are fractionated to varying extents, but those advocating a moderate pressure origin for the primary magmas believe that most or all of the fractionation history is displayed by the compositional variations of lavas erupted at the surface and that the extensive olivine fractionation required by those favoring picritic primary magmas has not taken place. Presnall et al. (1979) have noted that picritic MORB *glass* compositions apparently do not exist. However, Stolper and Walker (1980) have argued that primary and parental picritic liquids exist at depth but are not erupted at the surface because of their high density.

A curious aspect of the argument is the fact that although most of the experimental data obtained by proponents of both views is in moderately good agreement, the interpretations of these data differ markedly. The purpose of this paper is to examine the reasons for these sharp differences in interpretation of essentially similar data.

Analytical uncertainties

Before proceeding to comparisons among the compositions of MORB glasses and experimentally produced glasses, the

Table 1. Analytical differences for five FAMOUS basalt glasses analyzed at Massachusetts Institute of Technolgy (MIT) and Smithsonian Institution (SM)

	$2\sigma_{MIT}$[a]	$2\sigma_{SM}$[b]	MIT minus SM (wt.%)[c]				
			5255-1	5255-2	5255-3	5194-1	5194-2
SiO_2	0.4	0.70	−0.05	−0.06	−0.52	0.13	0.13
TiO_2	0.06	0.12	−0.03	−0.04	−0.08	−0.03	−0.05
Al_2O_3	0.4	0.30	0.47	0.17	0.11	−0.09	−0.21
FeO	0.2	0.34	−0.32	−0.41	−0.52	−0.19	−0.33
MgO	0.32	0.22	0.65	0.53	0.15	0.74	0.69
CaO	0.2	0.30	−0.28	−0.41	−0.26	−0.93	−0.87
Na_2O	0.2	0.08	0.42	0.33	0.01	0.06	0.09
K_2O	0.02	0.04	−0.03	−0.04	−0.01	−0.03	−0.04

[a] Frey et al. (1974), 2σ = two standard deviations
[b] Melson et al. (1976)
[c] SM values from W.B. Bryan (pers. comm. 1981), MIT values from Bryan and Moore (1977)

analytical uncertainties must be evaluated. All the comparisons of interest involve glass compositions analyzed by electron microprobe and the compositions are commonly plotted on normative triangular diagrams. Three types of diagrams have been used. Presnall et al. (1979) and O'Donnell and Presnall (1980) used the CIPW norm procedure and calculated the mineral proportions in mole percent. The normalized mineral proportions were then plotted on the front face (diopside-olivine-quartz) and base (plagioclase-olivine-quartz) of the tholeiitic portion of the basalt tetrahedron of Yoder and Tilley (1962). Similar procedures have been used by many others (for example, see Coombs 1963; Chayes 1972; Clague and Bunch 1976; Bryan 1979). Walker et al. (1979) and Stolper (1980) used a different algorithm for calculating mineral proportions for MORB compositions, but their procedure yields diagrams that differ only slightly from the CIPW normative diagrams. Elthon and Scarfe (1984) used a third algorithm (Elthon 1983), which gives diagrams somewhat different from those obtained by the other two procedures. We will compare analytical uncertainties on the diagrams of Presnall et al. (1979) and Elthon and Scarfe (1984), with the former being taken as similar to analytical uncertainties on the diagrams of Walker et al. (1979) and Stolper (1980). The importance of analytical uncertainties on the CIPW normative diagrams has been briefly mentioned elsewhere (Presnall et al. 1979; O'Donnell and Presnall 1980).

Two of the best and most productive microprobe laboratories that have published analyses of MORB glasses are those at the Massachusetts Institute of Technology and the Smithsonian Institution. Analytical uncertainties for each of these laboratories, as reported respectively by Frey et al. (1974) and Melson et al. (1976), are listed in the first two columns of Table 1. These uncertainties are not for individual spot analyses but rather for published analyses, each representing an average of several different spots from the same sample. The uncertainties for the two laboratories are similar and are taken as representative of high-quality data within a given laboratory. The remaining columns of Table 1 show differences in the analyses of five glass samples analyzed at both the Smithsonian and MIT laboratories.

Consider first the reported uncertainties within a single laboratory. To determine how these uncertainties appear on the two projected normative diagrams, pl-ol-q (an-ol-q

for the Elthon algorithm) and di-ol-q, we have generated two sets of data, each containing 2000 synthetic basalt compositions. The compositions for each set are normally distributed about a mean corresponding to the average Mt. Pluto magma composition of Bryan and Moore (1977), a composition considered by these authors to be representative of primitive FAMOUS basalt. A random number generator was used to select values for the oxide percentages, the standard deviations for one data set corresponding to those reported by the MIT laboratory and for the other set to those reported by the Smithsonian laboratory. For each composition, $Fe^{2+}/(Fe^{2+} + Fe^{3+})$ was set at 0.86 (Presnall et al. 1979). Melson et al. (1976) stated that analyses whose sums deviated from 100% by more than 1.5% were discarded, but in our synthetic data sets we have retained all the analyses regardless of their sum. Given the MIT and Smithsonian uncertainties (Table 1), it can be determined from statistical tables that the criterion of Melson et al. would be expected to cause the rejection of less than one analysis from the MIT data set and about two analyses from the Smithsonian data set. Thus, using this rejection criterion would not noticeably alter our results.

Figure 1 shows plots of the two data sets on the CIPW normative diagrams ol-di-q and ol-pl-q. It can be seen that the analytical uncertainties are greatest along a narrow region extending toward the quartz apex, a feature caused by the manner in which the CIPW norm is calculated. Uncertainties in SiO_2 do not contribute to variations in normative olivine, hypersthene, diopside, or plagioclase because SiO_2 is merely added to these minerals in quantities necessary to balance previously assigned amounts of the other oxides. On the other hand, uncertainties in SiO_2, Na_2O, Al_2O_3, CaO, MgO, and FeO all contribute to uncertainties in normative quartz because quartz is calculated last by difference. The form of the uncertainty distribution is approximately the same for both laboratories but is slightly greater in the long dimension for the MIT uncertainties. In an effort to present the most favorable case, only the Smithsonian uncertainties will be shown on subsequent diagrams.

Figure 2 shows the Smithsonian set of compositions plotted according to the procedure of Elthon (1983). For his algorithm, the plagioclase apex of Fig. 1, b and d becomes anorthite, and albite plots on the anorthite-quartz edge at 80% quartz, 20% anorthite. As pointed out by Elthon, his algorithm suppresses variation in normative quartz. Note also that the distributions are shifted toward quartz relative to those in Fig. 1.

Now consider the problem of systematic differences between laboratories. Existing data are adequate for two preliminary comparisons, one between the MIT and Stony Brook laboratories (Fig. 3, a) and one between the MIT and Smithsonian laboratories (columns 3–7 of Table 1 and Fig. 3, b). Figure 3, a shows no clear systematic differences between the MIT and Stony Brook data, and the differences are approximately of the same magnitude as those within a single laboratory. For the MIT and Smithsonian laboratories, differences are consistently of the same sign for all oxides except SiO_2 and Al_2O_3 (Table 1). Also, one of the Al_2O_3 pairs, two of the FeO pairs, four of the MgO pairs, three of the CaO pairs, and two of the Na_2O pairs differ by more than the supposed 2σ of either laboratory. Thus, it appears that a bias between the MIT and Smithsonian laboratories exists. This bias yields analyses from the MIT
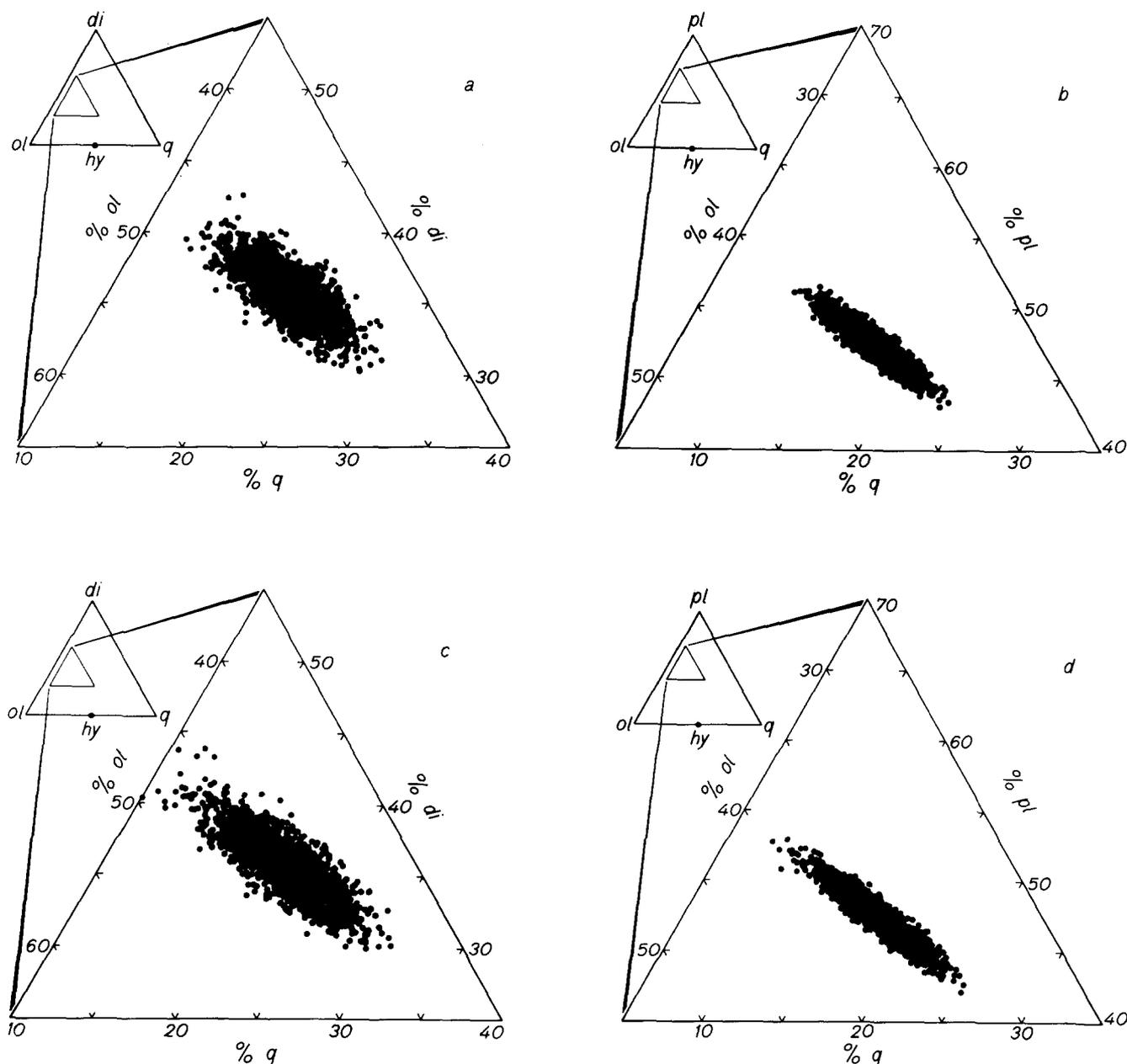
Fig. 1. Projections of synthetic analyses normally distributed about the Mt. Pluto (FAMOUS) average magma (Bryan and Moore 1977) based on microprobe analytical uncertainties from (diagrams a and b) the Smithsonian Institution (Melson et al. 1976) and (diagrams c and d) the Massachusetts Institute of Technology (Frey et al. 1974). Each diagram contains 2,000 points. Mineral proportions in mole percent are calculated according to the CIPW norm conventions. $pl = Na_2Al_2Si_6O_{16} + CaAl_2Si_2O_8$; $ol = Mg_2SiO_4 + Fe_2SiO_4$; $hy = MgSiO_3 + FeSiO_3$; $di = CaMgSi_2O_6 + CaFeSi_2O_6$; $q = SiO_2$. For compositions on this and all subsequent diagrams, $Fe^{2+}/(Fe^{2+} + Fe^{3+})$ is assigned the value 0.86 (Presnall et al. 1979). Diagrams are projections onto the ol-di-q face or onto the ol-pl-q face of the tholeiitic basalt tetrahedron ol-pl-di-q

laboratory that are consistently lower either in normative quartz or in diopside and anorthite than those from the Smithsonian laboratory (Fig. 3, b). Although the magnitude of the bias appears very large for some of the points on the diagram, it is in fact only marginally greater than the uncertainty within a single laboratory (compare Fig. 4).

When looking for compositional distinctions among different suites of natural glass analyses (for example, see Bryan and Dick 1982), there is little likelihood of dealing inappropriately with the analytical uncertainties as long as the sample populations are fairly large. However, when drawing petrogenetic conclusions from experimental data,

it is common to rely on analyses of only a very few experimental charges. Because it is not immediately obvious how uncertainties in an analysis translate to uncertainties on various normative mineral plots, there has been a tendency to suppose a higher precision on these diagrams than actually exists.

Evaluation of picritic parental magmas

In the light of the previous discussion of analytical uncertainties, we now evaluate some conclusions based on microprobe analyses of experimental and natural glass composi-
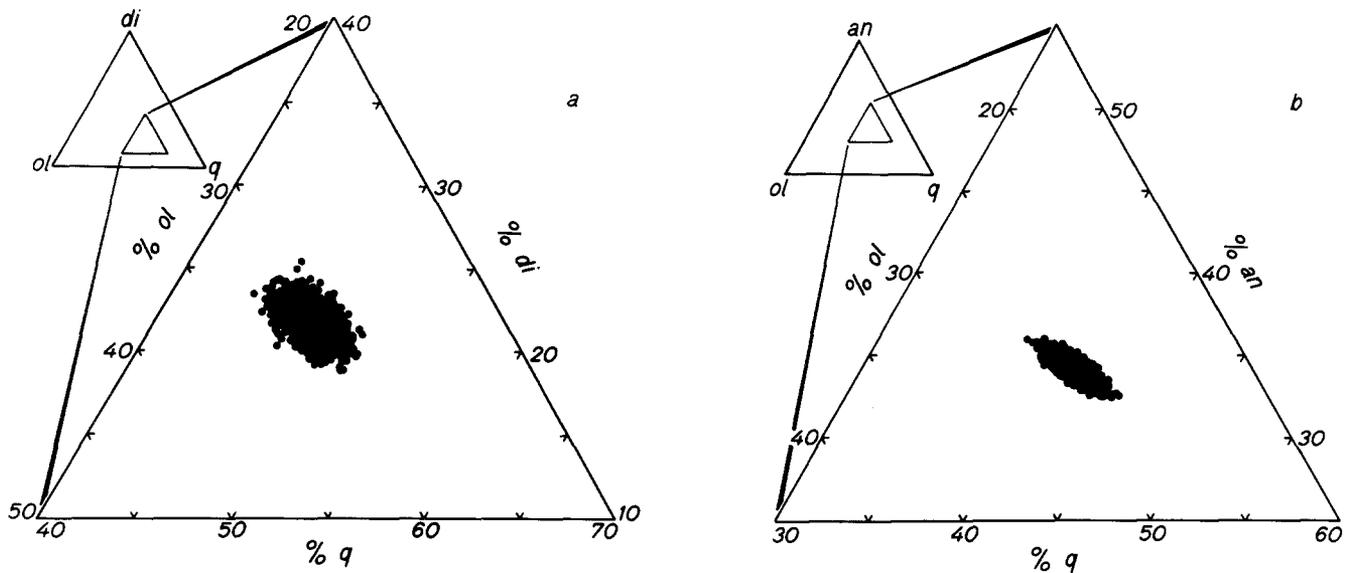
Fig. 2. Same data as in Fig. 1, *a* and *b* (Smithsonian uncertainties) with mineral proportions in mole percent calculated according to the algorithm of Elthon (1983). Note that for this algorithm the *pl* apex of Fig. 1 is replaced by *an* (anorthite)
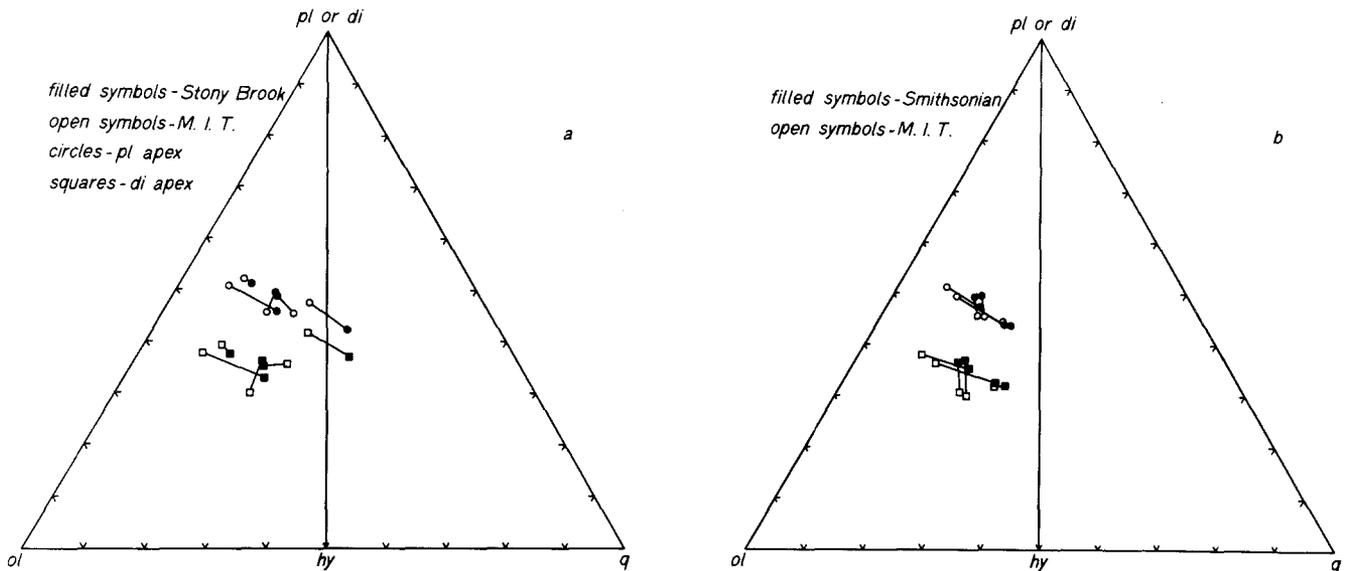

Fig. 3. CIPW norm projections (mole percent) of FAMOUS basalt glass samples analyzed at the State University of New York at Stony Brook (Langmuir et al. 1977), Massachusetts Institute of Technology (Bryan and Moore 1977), and the Smithsonian Institution (W.B. Bryan, pers. comm. 1981). Lines between points connect identical samples. Sample numbers (see Bryan and Moore 1977), are 5194-1, 5255-2, 5266-1, 5271-1, 5284-1 (diagram *a*) and 5194-1, 5194-2, 5255-1, 5255-2, 5255-3 (diagram *b*). In diagram *b*, MnO and Cr_2O_3 values for the MIT analyses are deleted because these oxides were not reported in the Smithsonian analyses

tions. Basalt glass analyses from the FAMOUS area of the Mid-Atlantic Ridge (Bryan and Moore 1977; Bryan 1979) will be taken as typical of MORB compositions in general. The FAMOUS data, all determined at a single laboratory (MIT), are plotted in Fig. 4. Superimposed on the FAMOUS data points are 2σ ellipsoids based on contouring of the Smithsonian uncertainties (Fig. 1).

It is generally agreed that the spread of basalt compositions is predominantly the result of fractionation of olivine, plagioclase, and diopside, the least fractionated basalts lying generally to the left and the most fractionated basalts lying generally to the right on all the diagrams (Clague and Bunch 1976; Presnall and O'Donnell 1976; Bryan and Moore 1977; Walker et al. 1979; O'Donnell and Presnall 1980; Elthon and Scarfe 1984). Although we agree with

this interpretation, it is apparent that a substantial part of the total variation of normative quartz[1] in the FAMOUS glass compositions may be attributed simply to analytical uncertainty. Because the direction of maximum analytical uncertainty on the normative diagrams essentially coincides with the compositional trend thought to be produced by fractional crystallization, the ability to resolve compositional changes along the fractionation trend is sharply reduced.

Figure 5 shows *mg* number versus percent quartz on

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1 In the remainder of this paper, the "quartz-rich" and "quartz-poor" ends of the FAMOUS array will refer to the entire distribution of points in Fig. 3, *a* and *b* as if normative hypersthene had been recast as equivalent olivine and quartz. This "elimination" of hypersthene does not cause any change in the positions of the plotted points
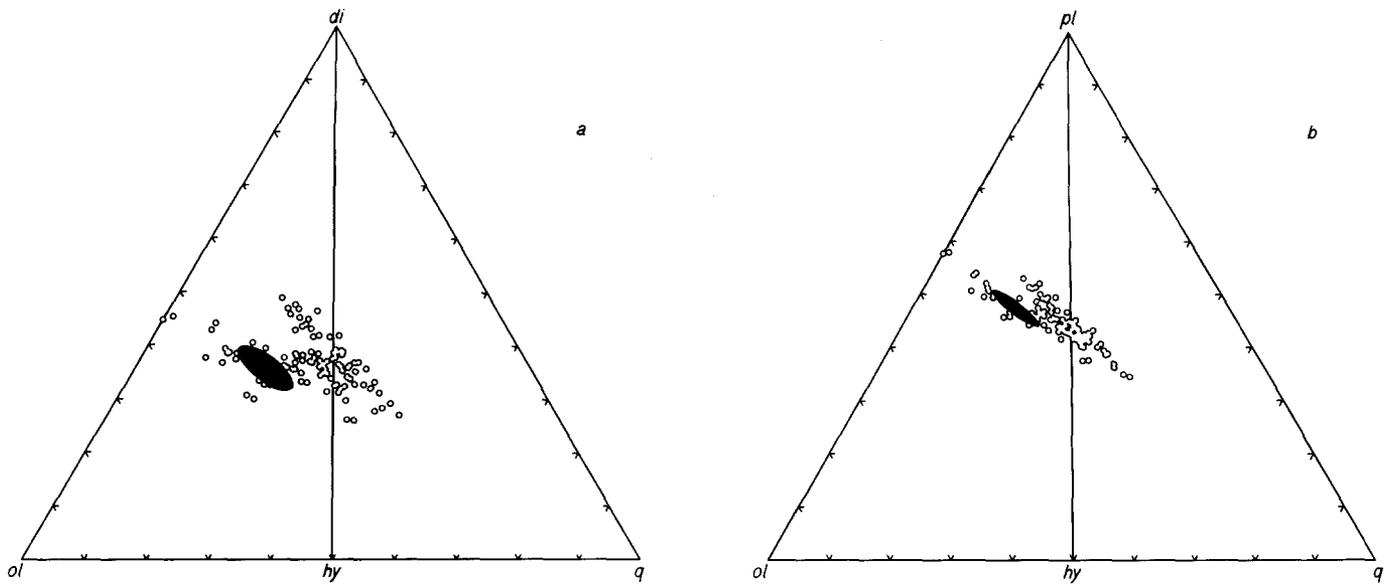
Fig. 4. CIPW norm projections (mole percent) of FAMOUS basalt analyses (Bryan and Moore 1977; Bryan 1979) and 2σ (95%) confidence ellipsoids based on contouring of the data shown in Fig. 1, a and b
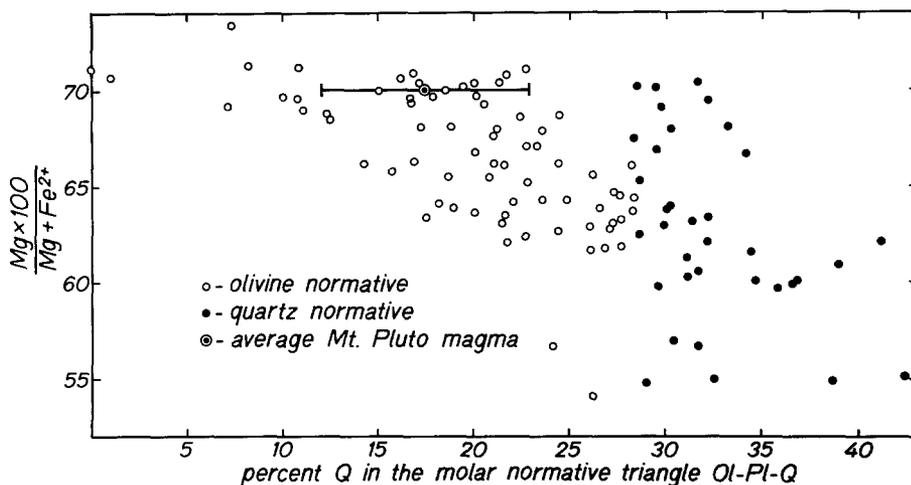

Fig. 5. Percent quartz in the molar CIPW normative triangle ol-pl-q versus $(100\ Mg)/(Mg + Fe^{2+})$ (mg number) for FAMOUS basalts plotted in Fig. 4, b. The double circle with bracket is the average Mt. Pluto magma (Bryan and Moore 1977) with 2σ confidence limits taken from Fig. 4. For the mg numbers, $2\sigma \simeq 1$ (Chayes 1971, p 27–28)

the CIPW normative triangle ol-pl-q. The mg numbers, although widely scattered, generally decrease with increasing normative quartz, which verifies that despite the large uncertainties, a major part of the MORB array is due to fractional crystallization.

Figure 6 shows experimentally determined liquid compositions in equilibrium with plagioclase-, spinel-, or garnet-lherzolite mineral assemblages at various pressures. These compositions represent potential primary magmas. The data by Presnall et al. (1979) are liquid compositions in equilibrium with model plagioclase lherzolite (<9 kbar) and spinel lherzolite (>9 kbar) in the system CaO-MgO-Al_2O_3-SiO_2 (CMAS). Presnall et al. argued that primary basalts at spreading ridges are generated at about 9 kbar and that the addition of other components to the CMAS system would shift the 9 kbar liquid composition in equilibrium with lherzolite away from silica to a position close to the least fractionated, left-hand end of the MORB array. On the basis of experiments with natural basalts, Stolper (1980) agreed with the direction of the shift of the 9 kbar liquid composition predicted by Presnall et al. but argued

that the shift was not great enough for primary magmas produced at this pressure (approximated by Stolper's 10 kbar point in Fig. 6) to explain the quartz-poor end of the MORB array. Stolper argued that picritic primary magmas produced at a pressure of at least 15 kbar, which would be low in normative quartz (Fig. 6), are needed to produce parental magmas at the quartz-poor end of the MORB array by crystallization of olivine.

Note that the compositional difference most critical to Stolper's argument corresponds to the direction of maximum analytical uncertainty. In addition, Stolper drew his phase boundaries by combining his own data with those of two other laboratories, and he compared these phase boundaries with MORB glass compositions determined at still another laboratory. The systematic differences among analyses from these four laboratories are not known. Except possibly for the two FAMOUS analyses lying at the extreme quartz-poor end of the FAMOUS array (Fig. 4, a and b), we feel that the analytical uncertainties are large enough to justify some doubt about Stolper's conclusions. It might be argued that these two points deviate sufficiently
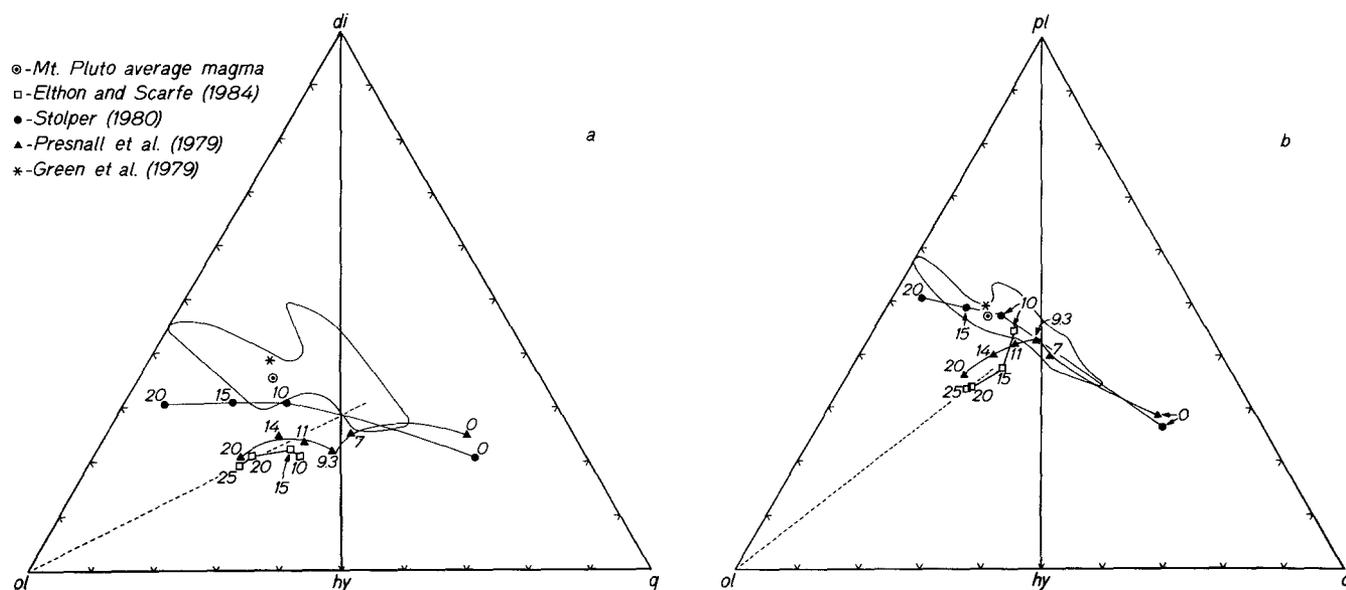
Fig. 6. Molar CIPW normative projections showing the outline of the FAMOUS basalt composition field from Fig. 4 (irregular contour) and experimentally determined liquid compositions in equilibrium with ol, opx, and cpx (also pl at pressures less than 10 kbar) (Stolper 1980); ol, opx, cpx, and sp (garnet replaces spinel at 25 kbar) (Elthon and Scarfe 1984); and ol, opx, cpx, and sp (plagioclase replaces spinel at pressures less than 9 kbar) (Presnall et al. 1979). Data of Stolper (1980) and Elthon and Scarfe (1984) are for natural compositions. Data of Presnall et al. (1979) are for the system $CaO-MgO-Al_2O_3-SiO_2$. Numbers are pressures in kbar. The point for Green et al. (1979) is a primitive basalt (their Table 1, Column 1). The dashed line in each diagram shows the direction of olivine fractionation from the 25 kbar point of Elthon and Scarfe (1984)

from Stolper's 10 kbar pseudoinvariant point that his conclusions must stand. However, other problems exist, as discussed below.

Now consider the data of Elthon and Scarfe (1984), which, like Stolper's data, are based on melting experiments on a natural basalt. Their liquid compositions in equilibrium with olivine, orthopyroxene, clinopyroxene, and either spinel (10, 15 and 20 kbar) or garnet (25 kbar) are plotted in Figs. 6 and 7. These data are a revision of their earlier data on the same basalt (Elthon and Scarfe 1980).

Elthon and Scarfe (1980, 1984) used the same line of reasoning as Stolper to claim that picritic primary magmas generated at about 25 kbar are required to produce the quartz-poor portion of the MORB array. Low-pressure crystallization of olivine would move liquid compositions along a line originating at their primary magma composition at 25 kbar and extending directly away from the olivine apex (dashed line in Figs. 6, *a* and *b*, 7, *a* and *b*). It can be seen in the CIPW normative projections (Fig. 6) that such a line would intersect the *quartz-rich* portion of the FAMOUS array. With subsequent crystallization of olivine, diopside, and clinopyroxene, the liquid path would move along the trend of the array toward quartz, thereby explaining compositions only in the quartz-rich portion. Compositions in the quartz-poor portion would remain unexplained even when analytical uncertainties are taken into account. Thus, the conclusions of Elthon and Scarfe appear to be contradicted by their own data. In fact, if their data are taken at face value, the quartz-poor portion of the FAMOUS array seems impossible to explain by fractionation of olivine from a primary magma separated from a lherzolite source region at *any* pressure!

On the other hand, when the data of Elthon and Scarfe are plotted using the algorithm of Elthon (1983), a picritic primary magma located at the composition of their 25-kbar

liquid does indeed appear capable of producing a parental basalt near the quartz-poor end of the FAMOUS array by crystallization of olivine (Fig. 7). This parental magma composition could then produce all the other FAMOUS basalts by fractionation of olivine, plagioclase, and clinopyroxene.

Why does olivine fractionation of Elthon and Scarfe's 25 kbar primary magma composition lead in one projection to the quartz-poor end of the FAMOUS array and in the other projection to the quartz-rich end? The answer lies in the fact that the magnitude of the shift toward quartz produced by the Elthon algorithm depends strongly on the amount of Na_2O in the composition. Note that the points of Presnall et al. (1979), which contain no Na_2O, do not change position at all when replotted according to the Elthon algorithm (compare Figs. 6 and 7). The FAMOUS compositions contain about twice as much Na_2O as Elthon and Scarfe's 25 kbar liquid and are therefore shifted more strongly toward quartz when the Elthon algorithm is used.

One must then ask which, if either, projection method yields valid conclusions about the result of olivine fractionation from Elthon and Scarfe's 25 kbar picritic magma. Eighteen of the FAMOUS basalts have *mg* numbers greater than 70 and constitute a set of least fractionated magma compositions that Elthon and Scarfe would presumably derive by olivine fractionation from their 25 kbar liquid. Crystallization of olivine would increase TiO_2 in any derivative magma, yet seventeen of the eighteen basalts have TiO_2 contents *lower* than that of the 25 kbar liquid (0.89 wt.%, analyses normalized to 100%). This relationship also holds for most primitive MORB compositions worldwide, whose TiO_2 contents converge at 0.6–0.9 wt.% at *mg* numbers of 70–73 (Rhodes and Dungan 1979). The 15 and 20 kbar liquids of Elthon and Scarfe are even higher in TiO_2 than their 25 kbar liquid, and therefore must also be rejected
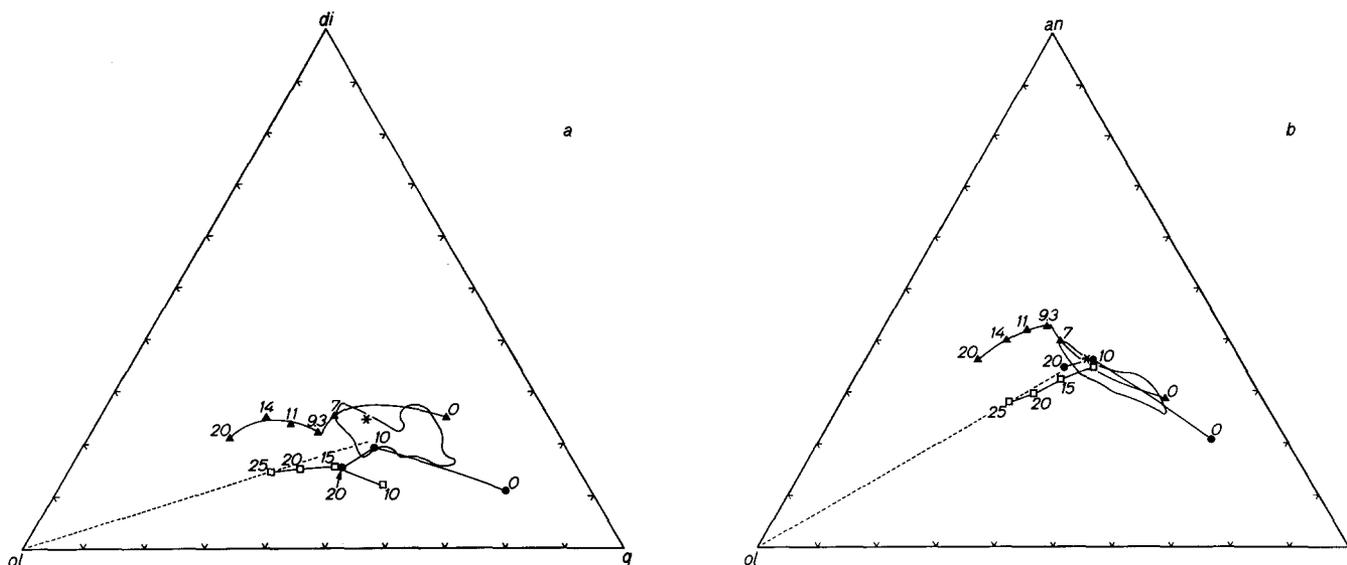
Fig. 7. Same data as Fig. 6 calculated according to the Elthon (1983) algorithm

as viable parental magmas. When least-squares mixing calculations (Wright and Doherty 1970) are attempted between Elthon and Scarfe's high pressure picritic liquids and the various least fractionated FAMOUS basalts, extremely poor fits are obtained not only for TiO_2 but also for Na_2O and sometimes other oxides. We conclude that primitive mid-ocean ridge basalts cannot be derived by olivine fractionation from Elthon and Scarfe's high pressure picritic magmas, and that neither projection scheme is a valid vehicle, by itself, for evaluating such a process.

In view of the inadequacy of the projected diagrams as vehicles for evaluating Elthon and Scarfe's parental liquid, we now return to Stolper's 20 kbar picritic parent. Olivine fractionation would lead to higher values of TiO_2 and Na_2O in the derived basalts yet at least one and frequently both of these oxides are higher in Stolper's 20 kbar liquid than in the eighteen primitive FAMOUS basalts. The TiO_2 content (0.87%) of Stolper's 20 kbar liquid is also higher than that of most primitive MORB compositions worldwide. Least-squares fits for the primitive FAMOUS basalts are all extremely poor. We conclude that primitive FAMOUS basalts as well as primitive mid-ocean ridge basalts worldwide cannot be derived by olivine fractionation from Stolper's 20 kbar parent.

Dimensions of "pseudoinvariant" regions

We have not discussed one source of uncertainty that is potentially the most important of all. As Stolper (1980) and Elthon and Scarfe (1984) mentioned, the "pseudoinvariant points" they determined at each pressure are not points but regions in multicomponent composition space. The dimensions of these regions are unknown, but a comparison of the data of Stolper (1980) and Elthon and Scarfe (1984) on Fig. 6 suggests that they could be very large. In making this comparison, it should be noted that Elthon and Scarfe's liquids are in equilibrium with spinel whereas Stolper's are not. Thus, a precise comparison is not possible; but we suggest, on the basis of data for the CMAS system (Presnall et al. 1979) and Fig. 4 of Fujii and Bougault (1983), that in Stolper's study the spinel field would lie to the silica-poor side of his spinel-free pseudoinvariant points. This implies

that the pseudoinvariant regions in Fig. 6 have dimensions even larger than the differences between the points of Elthon and Scarfe and those of Stolper. The size of these regions could, of course, vary strongly as a function of pressure.

Takahashi and Kushiro (1983) show lines at constant pressure rather than pseudoinvariant points. The points of Stolper (1980) and Elthon and Scarfe (1984) lie along the lines of Takahashi and Kushiro; and if the interpretation of Takahashi and Kushiro is correct, the data of all three papers are in fairly good agreement. In this case, the liquid compositions reported by Elthon and Scarfe would be produced by a higher degree of melting than those reported by Stolper.

Location of the enstatite field at high pressures

O'Hara (1968) emphasized that primary magmas generated from a peridotite mantle must be in equilibrium with enstatite at their depth of origin. Therefore, if any basalts erupted at spreading centers are unfractionated primary magmas, the MORB array must touch the primary phase field of enstatite. O'Hara argued that it does not, and that all mid-ocean ridge basalts are therefore fractionated from more primitive parents. Specifically, he argued that primary mid-ocean ridge basalts are not produced at about 10 kbar.

Stolper's (1980) recent determination of the position of the enstatite field at 10 kbar, as shown by his pseudoinvariant point, is analytically indistinguishable from the average Mt. Pluto magma (Fig. 6), a composition considered by Bryan and Moore (1977) to approximate the least fractionated basalts from the FAMOUS area. The revisions of Stolper's phase boundaries by Fujii and Bougault (1983) move the 10-kbar pseudoinvariant point even closer to the Mt. Pluto magma composition. Thus, when the phase boundaries of either Stolper or Fujii and Bougault are compared to the Mt. Pluto magma composition, O'Hara's argument fails.

In a study of high-pressure crystallization of a primitive MORB, Green et al. (1979) found at 12 kbar that enstatite does not crystallize at the liquidus and that addition of 5–10% enstatite to the mixture is necessary before liquidus

enstatite appears. They concluded from these results that the basalt could not have been in equilibrium with enstatite at high pressures and therefore is not primary. This reasoning was accepted by Elthon and Scarfe (1984), but Wyllie et al. (1981, p 510–512) showed theoretically that it is invalid to conclude from the absence of liquidus enstatite that the liquid could not have been in equilibrium with enstatite. Furthermore, Wyllie et al. showed that topologies are theoretically possible in which a liquid composition can be in equilibrium with enstatite at some pressure yet enstatite would not appear at the liquidus at that pressure *regardless* of the amount of added enstatite component (see also discussion by Fujii and Bougault 1983). Wyllie et al. (1981) also pointed out that if a phase *is* found at the liquidus, one can conclude that the composition in question is saturated with that phase. Fujii and Bougault (1983) found enstatite at the liquidus at 10 kbar for their basalt.

The experiments of Stolper (1980) suggest that the pseudoinvariant point liquid in equilibrium with olivine, enstatite, diopside and spinel at 10 kbar is, in fact, only marginally distinguishable by microprobe analytical techniques from the primitive MORB composition of Green et al. (Fig. 6). If the revised position of Stolper's 10 kbar pseudoinvariant point proposed by Fujii and Bougault (1983) is accepted, the composition of Green et al. is sensibly identical to that of the pseudoinvariant point liquid.

Given the analytical uncertainties we have documented, the position of the enstatite field determined at various pressures by Takahashi and Kushiro (1983) is in good agreement with the studies of Stolper (1980), Fujii and Bougault (1983), and Elthon and Scarfe (1984), and is fairly consistent even with the seemingly discrepant results of Jaques and Green (1983) (see Fig. 13 of Takahashi and Kushiro 1983). Thus, we consider that the weight of evidence is strongly in favor of the conclusion that the enstatite field at about 10 kbar lies close to the field of primitive mid-ocean ridge basalts.

Multiple parental magmas and depth of origin

Figure 5 shows that the least fractionated basalts with *mg* numbers greater than 70 have a very wide range of normative quartz content, which exceeds by a factor of two even the large uncertainty brackets shown. Thus, although most of the least fractionated basalts lie in the quartz-poor portion of the FAMOUS array, there are a significant number in the central and quartz-rich portions that are less fractionated than some of the basalts that lie in the quartz-poor region. This feature is inconsistent with derivation of the entire array from a common parent at the quartz-poor limit of the array. Multiple parental magmas having a range of normative quartz content appear necessary, which implies that the array as a whole is a composite mixture of several overlapping fractionation trends. Multiple parental magmas in the FAMOUS area have been suggested also by many others (Bougault and Hekinian 1974; Bryan and Thompson 1977; Langmuir et al. 1977; Bryan 1979; LeRoex et al. 1981; Bryan 1983; Grove and Bryan, 1983).

The data of Takahashi and Kushiro (1983) suggest that it would be possible, by varying the amount of melting, to produce high-pressure picritic primary melts of differing normative quartz content.[1] The geometry of Fig. 6 suggests

that subsequent low-pressure fractionation of olivine from these different picritic melts would yield liquid paths intersecting the FAMOUS array over much of its length. Such parents for mid-ocean ridge basalts would, of course, require confirmation in any given case by least-squares mixing calculations, a confirmation, as we have already noted, that does not exist for the picritic liquids of Stolper (1980) and Elthon and Scarfe (1984). If the least-squares mixing test is passed, some of the basalts lying in the central to quartz-rich portion of the FAMOUS array could conceivably be fractionated not from liquids lying in the low-quartz portion of the FAMOUS array but rather from picritic liquids more enriched in normative quartz than those proposed by Stolper (1980).

Presnall et al. (1979, p 26) concluded from phase relationships in the system $CaO - MgO - Al_2O_3 - SiO_2$ that primary magmas beneath ridges are generated over a small pressure range centered at about 9 kbar. On the basis of phase relationships involving the addition of Na_2O to this 4-component system (Hoover and Presnall 1981, 1982), we suggest that the most likely pressure range is from about 7 to 11 kbar, a pressure range that can adequately explain the existence of multiple parental magmas with widely varying normative quartz contents (Fig. 5). Presnall et al. (1978) suggested that the orthopyroxene field extends into the nepheline-normative field at pressures above about 12 kbar. Thus, alkalic primary magmas could be generated beginning at this pressure. Our recent results (Hoover and Presnall 1981, 1982) and those of Takahashi and Kushiro (1983) generally support this earlier estimate and suggest that the lower pressure limit for the generation of alkalic primary magmas should be lowered slightly to about 11 kbar. Liquid compositions produced at 10–11 kbar lie close to the silica-poor end of the FAMOUS array. Thus, to produce parental magmas anywhere along the central to quartz-poor part of the FAMOUS array, pressures of magma generation from about 7–11 kbar appear entirely adequate. Figure 6 suggests that picritic parental magmas are possible, but this possibility is denied by the absence to date of experimentally produced picritic liquids that pass least-squares mixing tests.

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1 See earlier footnote

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