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Composition and depth of origin of primary mid-ocean ridge basalts – reply to D. Elthon*

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Introduction. Elthon (1986) has disputed our conclusion that the arguments favoring the derivation of mid-ocean ridge basalts from picritic primary magmas are inadequate (Presnall and Hoover 1984). He makes four assertions.

1. The microprobe analytical uncertainties we showed are much larger than uncertainties achieved by most investigators.
2. We misstated the TiO_2 abundances of primitive mid-ocean ridge basalts, with the result that our arguments against the parental nature of the picritic compositions of Stolper (1980) and Elthon and Scarfe (1984) are weakened.
3. Least-squares mixing calculations are not a valid test of the viability of picritic parental magmas because these calculations evaluate only equilibrium crystallization processes. Also, we failed to consider other more complex models of magmatic evolution such as high-pressure crystallization and magma mixing that are relevant to the petrogenesis of mid-ocean ridge basalts.
4. Our discussion of the relationship between enstatite saturation and primary magmas generated from the mantle does not apply to the pressure range at which mid-ocean ridge basalts are generated.

In the discussion that follows, we address each of these criticisms in turn. Criticism 3 listed here is a combination of his criticisms 3 and 4. In his criticism 4, he includes a discussion of the Na_2O content of primitive mid-ocean ridge basalts, but we have separated part of our discussion of Na_2O and included it at the end of our reply. As will be seen in the discussion that follows, some of the criticisms of Elthon (1986) are factually incorrect, and none of them causes us to retract or soften any of our earlier conclusions. To the contrary, Elthon's remarks have spurred us to pursue certain aspects of our earlier arguments that we believe strengthen the conclusions in Presnall and Hoover (1984).

1 Analytical uncertainties

Elthon argues that our use of the published standard deviations of the MIT and Smithsonian microprobe laboratories is inappropriate because he believes that these standard deviations refer to the variability of individual spot analyses whereas most investigators publish more precise analyses that are averages of 5 to 10 spots.

We stated (Presnall and Hoover 1984, p 171) that the MIT and Smithsonian standard deviations apply to averaged analyses, not individual spot analyses. After further discussions with W.B. Bryan, we now realize that for the MIT uncertainties (Frey et al. 1974), this statement is incorrect. The MIT standard deviations are, in fact, based on about 15 spot analyses of three different chips of basalt glass standard VG-2 of the Smithsonian Institution (W.B. Bryan personal communication). Thus, Elthon's understanding of the meaning of the MIT uncertainties is approximately correct. However, recent discussions with W.G. Melson, E. Jarosewich, and T. O'Hearn confirm our original understanding that the Smithsonian standard deviations (Melson et al. 1976) refer to the variability of a population of *averaged analyses* accumulated over a period of months. Each such analysis is the average of at least 5 individual spot analyses taken during a single analytical run (T. O'Hearn personal communication). Thus, Elthon's assumption about the manner in which the Smithsonian uncertainties were constructed is incorrect. Note that none of the petrologic conclusions in Presnall and Hoover (1984) were based on the MIT uncertainties: our conclusions were all based on the Smithsonian uncertainties. Thus, the uncertainty envelopes we showed (Presnall and Hoover, Fig. 1a and b; Fig. 2) are directly relevant to microprobe analyses typical of those published by most petrologists, and our conclusions stand as originally stated.

Elthon (1986, Fig. 1) shows a hypothetical representation of the much smaller uncertainties he expects for averaged analyses in comparison to those for individual spot analyses. As mentioned above, the MIT and Smithsonian uncertainties apply to each of the two cases shown by Elthon, and it can be seen from Fig. 1a–d of Presnall and Hoover (1984) and Table 1 that Elthon's expectations are not sustained. Uncertainties for the two types of populations are, in fact, very similar. Evidently, the increase in precision produced by averaging several spot analyses is approximately counterbalanced by new errors introduced from instrumental and operator variations over longtime periods. Elthon's expectations would hold only on the assumption that instrumental and operator variations over long periods of time (months) are negligible, an assumption that is shown clearly by the Smithsonian data to be incorrect.

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Table 1. 2σ uncertainties for single spot and averaged electron microprobe analyses from various laboratories[a]

	MIT (15)	MIT (10)	USGS (10)	SM (7)	SM (average)
SiO_2	0.4	0.92	1.16	1.02	0.70
TiO_2	0.06	0.05	0.10	0.08	0.12
Al_2O_3	0.4	0.32	0.60	0.36	0.30
FeO	0.2	0.32	0.45	0.18	0.34
MgO	0.32	0.18	0.28	0.30	0.22
CaO	0.2	0.15	0.41	0.30	0.30
Na_2O	0.2	0.23	0.27	0.12	0.08
K_2O	0.02	0.01	0.11	0.04	0.04

[a] MIT, Massachusetts Institute of Technology, USGS, US Geological Survey; SM, Smithsonian Institution
Columns 1–4 show the variability of single spot analyses of Smithsonian basalt standard VG-2 (number of analyses given in parentheses). For columns 2–4 Kakanui hornblende was used as a standard. Column 5 shows the variability of averaged analyses, each analysis being the average of at least five single spot analyses. Column 1 is from Frey et al. (1974). Columns 2–4 are from Jarosewich et al. (1979) and are averages of two, two, and four runs respectively. Column 5 is from Melson et al. (1976b)

The data in Table 1 provide further documentation. Columns 1–4 show uncertainties *within a single analytical run* for individual spot analyses from three different microprobe laboratories, with the magnitude of the MIT uncertainties confirmed by two different studies (columns 1 and 2). Column 5 shows the Smithsonian uncertainties for a population of *averaged analyses*. Columns 1 and 5 are the uncertainties on which our paper (Presnall and Hoover 1984) was based. In this table, it can be seen that the long-term Smithsonian uncertainties for averaged analyses are (coincidentally) similar to the Smithsonian uncertainties for individual spot analyses in a single analytical run, and that the precision obtained at the Smithsonian facility is typical of that at other installations. We agree with Elthon that long-term uncertainties of averaged analyses are the most meaningful for petrologic interpretations, but the only published uncertainties of this type that are based on actual experience are those of the Smithsonian Institution (Melson et al. 1976) shown in Presnall and Hoover (1984, Fig. 1a and b). In the face of these data, the hypothesized uncertainties of Elthon (1986) must yield.

2 TiO_2 abundances

Elthon (1986) claims that "... many primitive MORBs have TiO_2 abundances higher than 0.87%...", and that this "substantially weakens" our argument, based on TiO_2 abundances (Presnall and Hoover 1984, pp 175–176), that most primitive mid-ocean ridge basalts cannot be derived by fractional crystallization of the experimentally produced picritic primary liquid of either Stolper (1980) or Elthon and Scarfe (1984).

According to Elthon (1986), references in which "many primitive MORBs" may be found with TiO_2 greater than 0.87% are Melson et al. (1976b), Flower et al. (1983), Bender et al. (1984), Rhodes et al. (1979), and Emmermann and Puchelt (1980). In Presnall and Hoover (1984, p 175) primitive basalts were taken to be those with *mg* numbers >70 ($mg = \mathrm{Mg} \times 100/(\mathrm{Mg}+\mathrm{Fe}^{2+})$), with Fe^{2+} calculated on the assumption that $\mathrm{Fe}^{2+} = (0.86)$ (total Fe) (O'Donnell and Presnall 1980). Also, only glass compositions were considered. We have searched the references cited by Elthon for basalt analyses that meet these criteria, but we have relaxed the requirements so as to include not just glass compositions, but any analysis of a lava free of phenocrysts. On the basis of these criteria, we find three primitive basalt analyses in Melson et al. (1976b) and two in Flower et al. (1983). Bender et al. (1984), Rhodes et al. (1979), and Emmermann and Puchelt (1980) list no analyses that meet our criteria for a primitive basalt.

As a criterion for deciding if these five primitive basalts have TiO_2 contents greater or smaller than 0.87%, we use the Smithsonian uncertainty given in column 5 of Table 1. That is, the basalt must deviate by at least 2σ (0.12%) from 0.87%. By this criterion two of the five basalts have $TiO_2 < 0.87\%$ and therefore could not be derived by fractional crystallization from the picritic parental basalts of either Stolper (1980) or Elthon and Scarfe (1984). The other three basalts have TiO_2 contents analytically indistinguishable from 0.87%; contrary to the assertion of Elthon (1986), none of the basalts have a TiO_2 content clearly greater than 0.87%.

Two other oxides that would increase in residual liquids are Na_2O and K_2O. When these oxides are included and considered in the same way as we have treated TiO_2, we find that none of the five primitive basalts could be derived by fractional crystallization from Stolper's (1980) picritic parent. Two could not be derived from the 25 kbar picritic parent of Elthon and Scarfe (1984), and three are equivocal. An analysis is considered to be equivocal if none of the oxides, TiO_2, Na_2O, and K_2O, is clearly less than that of the corresponding oxide in the 25 kbar picritic liquid of Elthon and Scarfe (1984), but at least one of these oxides is analytically indistinguishable (and therefore *possibly* less). Thus, some of the data in the papers cited by Elthon strongly support our position, and some of the data are equivocal. None of these data clearly support Elthon's position.

In order to clarify further the issue of TiO_2, K_2O, and Na_2O contents in primitive mid-ocean ridge basalts, we have conducted a wider literature search. In an analytical program directed by W.B. Melson, the Smithsonian Institution has accumulated a file of about 1,000 microprobe analyses of mid-ocean ridge basalt glasses from the Atlantic, Pacific, and Indian Oceans (Melson et al. 1976a). Six[1] analyses from this file meet our criteria for a primitive basalt. Also, we have found three analyses of primitive basalt glasses in Frey et al. (1974), one in O'Donnell and Presnall (1980), one in Sigurdsson (1981), two in Fujii and Bougault (1983), two in Natland and Melson (1980), and 4 unpublished Pacific analyses (M.R. Perfit personal communication). These analyses together with the 18 analyses of primitive basalts from the FAMOUS area discussed in Presnall and Hoover (1984) and the 5 analyses in Melson et al. 1976b and Flower et al. 1983, give a total of 42 primitive basalts. When the analytical uncertainties of Table 1, column 5 are used is above, we find that for 41 of these basalts, the percentage (normalized to a total analysis of 100%) of at least one of the oxides, TiO_2, Na_2O, and K_2O, is clearly lower than that of the corresponding oxide in

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[1] One additional analysis in this file is duplicated in Melson et al. (1976b).

Stolper's (1980) 20 kbar picritic parent. Thus, Stolper's 20 kbar picritic liquid is an unsuitable parent for these basalts by any reasonable scheme of fractional crystallization. An even more decisive feature of Stolper's picritic parent is its *mg* number of 67.7 (assuming that $Fe^{2+}/(Fe^{2+}+Fe^{3+}) = 0.86$), which eliminates it as a possible parental liquid for all 46 primitive basalts.

When the TiO_2, Na_2O, and K_2O contents of the 25 kbar picritic liquid of Elthon and Scarfe (1984) are compared to the 42 primitive basalts, the results are also unfavorable to Elthon's position. Fourteen of the basalts could not be derivative liquids, one could be a derivative liquid, and 27 are equivocal. Of the 14 basalts that could not be derivative liquids, 13 are excluded based on their TiO_2 content. If the equivocal basalts are evenly divided, 28 basalts are excluded as derivative liquids and 14 could be derivative liquids. Thus, fractional crystallization of the 25 kbar picritic liquid of Elthon and Scarfe (1984) fails as a general mechanism for the production of primitive mid-ocean ridge basalts. Undoubtedly, our survey has not been exhaustive, but on the basis of the very large number of analyses searched, we feel it is representative.

3 Least-squares mixing calculations and complex models of magmatic evolution

Elthon (1986) rejects our use of least-squares mixing calculations to test the validity of various primary magmas. He states that "... least-squares solutions are valid only if perfect equilibrium crystallization has been the *only* process that has been operative ...". Elsewhere, he states that Presnall and Hoover "... do not consider the effects of complex models of magmatic evolution that incorporate processes such as high-pressure crystallization or magma mixing." He contends that "if these processes operate in a mid-ocean ridge environment, least-squares refinements are not valid for evaluating liquid lines of descent."

Several comments need to be made. First, it is clearly incorrect to assert that least-squares calculations are incapable of evaluating high-pressure crystallization processes. The calculations require only the input of melt and crystal compositions and can be used for crystallization at any pressure. Also, least-squares calculations are quite capable of dealing not only with equilibrium crystallization but with magma mixing processes as well as a stepwise approximation to fractional crystallization. We emphasized the importance of least-squares calculations to the evaluation of olivine fractionation models because olivine crystallization has been considered to be the most important mechanism for deriving mid-ocean ridge basalts from presumed picritic parents (O'Hara 1965, 1968; Green et al. 1979; Stolper 1980; Elthon and Scarfe 1984). For example, Elthon and Scarfe (1984, p 12) "... interpret the observation that most of the "primitive" oceanic basalts with >9.5% MgO are close to *olivine-controlled* liquid lines of descent from the 15 to 25 kbar isobaric pseudo-invariant points to indicate that those basalts have been derived from primary magmas generated within this pressure interval" (italics added). Elthon cannot simultaneously invoke olivine crystallization to support his picritic primary magma model and reject it to avoid quantitative accounting by least squares calculations of the consequences of olivine crystallization.

This difficulty aside, the questions Elthon raises about high pressure crystallization and magma mixing are important and should be considered. First, consider high-pressure crystallization. Elthon's contention is that the least-fractionated of the observed mid-ocean ridge basalt glasses could be derived by crystallization at high pressures from a picritic parent magma. Presnall and Hoover (1984) used least-squares calculations to test the simplest and most frequently proposed scenario of olivine crystallization and found it deficient when applied to the experimentally determined picritic parents of Stolper (1980) and Elthon and Scarfe (1984). The conclusions we reached would hold regardless of the pressure at which the olivine crystallizes and, to a first approximation, regardless of whether the process is equilibrium or fractional crystallization. Various combinations of other phases crystallizing at high or low pressures might be imagined and could easily be tested by least-squares calculations, but unless arguments can be given for reducing the TiO_2, Na_2O, and K_2O contents of the assumed picritic parent, we see no obvious alternative combination of crystallizing phases that would yield a successful test. The difficulties with TiO_2, Na_2O, and K_2O might be avoided for a small subset of primitive mid-ocean ridge basalts with high values for these oxides, but the overwhelming majority of primitive mid-ocean ridge basalts would continue to be unexplainable by fractional crystallization of the picritic liquids proposed by Stolper (1980) and Elthon and Scarfe (1984).

Now consider magma mixing. This process probably occurs to some extent at mid-ocean ridges, but it is not a likely process for generating the most primitive MORB glasses when either Stolper's or Elthon and Scarfe's picritic parental magma is taken as one of the magmas being mixed. As shown above, the amount of at least one of the oxides, TiO_2, Na_2O, and K_2O, in most of the primitive MORB glasses is lower than that of the corresponding oxide in either Stolper's (1980) or Elthon and Scarfe's (1984) proposed picritic parental magma. Crystal fractionation of one of these parental picrites would invariably produce a derivative magma with still higher TiO_2, Na_2O, and K_2O contents. Thus, magma mixing between the picritic parent and a derivative magma fractionated from an earlier similar picritic parent would be incapable of producing a mixture with a TiO_2, Na_2O, or K_2O content lower than that of the picritic parent. Until evidence is presented for the existence of picritic parental magmas low in all of these oxides, we feel that magma mixing cannot be sustained as a mechanism for producing the majority of the most primitive MORB glasses.

A final matter relating to Elthon's "complex model of magmatic evolution" concerns his remark that "the crystallization of even very small amounts of ilmenite will greatly complicate the interpretations of the TiO_2 abundances in MORBs and will render the TiO_2 residuals in least-squares calculations meaningless unless ilmenite is used." He considers ilmenite crystallization to be locally important because he finds ilmenite as a cumulus phase in abyssal gabbroic rocks, but he states that the associated olivine in these rocks has a maximum forsterite content of only 86.6%. The very primitive MORB glasses under consideration here with $mg > 70$ would be in equilibrium with olivine having a forsterite content $> Fo_{88.6}$ (Roeder and Emslie 1970). Thus, by Elthon's own documentation, ilmenite would not crystallize from picritic parental magmas to produce the most primitive MORB glasses with $mg > 70$, and none of our least-squares calculations would be affected.

4 Enstatite saturation

Elthon (1986) continues to believe that "the experiments of Green et al. (1979) indicate that the magma composition they studied was not enstatite-saturated and was not a primary magma, ..." In our discussion of this matter (Presnall and Hoover 1984, pp 176–177), we reemphasized the demonstration by Wyllie et al. (1981, pp 510–512) that enstatite-addition experiments coupled with the absence of liquidus enstatite cannot definitively establish that a melt composition is not saturated with enstatite. Such data are simply not adequate to define the phase relationships in multicomponent space immediately surrounding the liquid in question. We stand on our previous discussion of this matter and invite the reader to review our arguments and those of Wyllie et al. (1981).

Elthon (1986) makes the assertion that "at pressures relevant to the origin of primary MORBs (>9 kbar), ..., enstatite-addition lines drawn from isobaric pseudo-invariant points lie within the enstatite primary phase volume ...", and for data in support of this assertion, he refers to Stolper (1980) and Fujii and Bougault (1983). Both of these references show simplified and therefore not completely rigorous representations of the phase relationships in multicomponent space. At the present time, data adequate to support (or deny) Elthon's assertion are not available, and the issue is made especially problematical by the fact that critical enstatite-addition lines lie at a small angle to the olivine-enstatite boundary (Fujii and Bougault 1983, Fig. 3).

In fact, the basalt studied by Green et al. (1979) may not be saturated with enstatite, as they and Elthon claim. We argue only that the data of Green et al. (1979) are inadequate to establish this assertion definitively. Even if Green et al. (1979) are correct, we believe that their basalt composition lies so close to the enstatite field (see discussion in Presnall and Hoover 1984, p 177) that Elthon's claim of non-saturation is merely a technical objection that has no substantive effect on our conclusions.

5 Na_2O content of primary magmas

Subsequent to the preparation of our paper (Presnall and Hoover 1984), two papers have appeared that argue in favor of low Na_2O in magmas parental to primitive mid-ocean ridge basalts (Fisk 1984; Elthon and Casey 1985). Fisk (1984) noted the existence of anorthitic (An_{90-95}) plagioclase in some mid-ocean ridge basalts and argued that a coexisting liquid would need a CaO/Na_2O ratio of at least 10.0. Elthon and Casey (1985), noting the occurrence of anorthitic plagioclase and the existence of glass inclusions in spinels from mid-ocean ridge basalts that have Na_2O as low as 1.4%, argue that some primary oceanic basalts have very low Na_2O in the range 0.60 to 1.5 wt %. Elthon (1986) cites these papers and notes that most primitive mid-ocean ridge basalts are higher in Na_2O (1.9–2.5%) and have CaO/Na_2O ratios much less than 10. He argues that these primitive mid-ocean ridge basalts are derived by magma mixing and high pressure crystallization from parental magmas low in Na_2O. Presumably, he has not completely abandoned olivine crystallization as a means of deriving primitive mid-ocean ridge basalts from picritic parental magmas, but this is not clear from his discussion.

In our list of 42 primitive mid-ocean ridge basalts, the Na_2O content ranges from 1.43 to 2.49%, a range approximately the same as but somewhat wider than that noted by Elthon. Note especially the extension to considerably lower Na_2O contents. We feel that the evidence for the existence of some parental liquids low in Na_2O and with a high CaO/Na_2O ratio is good, but we see no evidence that the majority of primitive mid-ocean ridge basalts requires such a parent. We argued strongly for the existence of multiple parental magmas generated in the pressure interval of 7 to 11 kbar (Presnall and Hoover 1984, p 177), and it seems quite reasonable that some of these would have CaO/Na_2O ratios compatible with the crystallization of very Ca-rich plagioclase. In fact, Melson et al. (1976, p 359) list one glass analysis from the Indian Ocean of a primitive basalt with a Na_2O content of 1.43% and a very high CaO/Na_2O ratio of 9.5. This glass essentially matches Elthon's requirements for a low-Na_2O parental magma, but it has an *mg* value (70.3) similar to and in many cases slightly *lower* than those of other primitive mid-ocean ridge basalts. Thus, we believe that this low-Na primitive lava is not a suitable parent from which other, more typical, primitive lavas could be derived by magma mixing or fractional crystallization. We note also that this low-Na lava is not picritic.

In his concluding paragraph, Elthon (1986) states that he does "... not consider that a definitive test for whether MORBs are derived from high-MgO basalts depends on the acceptability of any particular high-MgO basalt composition such as NT-23[2] ..." Elthon apparently wishes to downgrade the importance of our arguments that the experimentally produced picritic melt of Elthon and Scarfe (1984)[2] is an unsatisfactory parent for most primitive mid-ocean ridge basalts, but in so doing, he also downgrades the importance of his own experimental work (Elthon and Scarfe 1984), which constitutes a major underpinning of his picritic primary magma model. We pointed out (Presnall and Hoover 1984, p 177) that picritic melts possibly exist that are parental to primitive mid-ocean ridge basalts, so we are in complete agreement with Elthon that our arguments are not "definitive" regarding the parental nature of picrites. Even though we believe that the experimental data of Stolper (1980) and Elthon and Scarfe (1984) do not support the picritic primary magma model, it might be possible to produce experimental picritic liquids that support this model if the source composition melted were sufficiently low in TiO_2, K_2O, and Na_2O, or if the percentage of melting were sufficiently large to reduce the concentrations of these oxides in the melt to acceptable values.

We wish to stress two main points. 1. Experimental data presently available on model systems indicate that the compositions of the most primitive MORB glasses are consistent with an origin as unfractionated or only slightly fractionated primary magmas generated at pressures less than about 11 kbar. 2. The compositions of these glasses as a group cannot be derived from the experimentally-produced picritic liquids of Stolper (1980) or Elthon and Scarfe (1984) either by fractional crystallization at high or low pressures or by magma mixing.

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[2] Basalt NT-23 is the sample used in the experiments of Elthon and Scarfe (1984) to produce a picritic melt

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