Iceland Mantle Plume

O'HARA[1] has objected to my interpretation concerning the trace element chemistry of lavas erupted along the Iceland-Reykjanes Ridge System[2] on the ground that: (1) Such magmas are not "primary magmas" but residual liquids; (2) instead, such lavas have suffered prior to eruption extensive "gabbro fractionation" at low pressure (olivine-augite-plagioclase extraction), and/or "eclogite fractionation" at higher pressure (clinopyroxene-garnet extraction in a 50–50% mixture); (3) the "extent of fractionation" is directly proportional to the elevation of the surface on which these lavas have been erupted, thus increases toward Iceland, and is the principal cause of trace element variations along the ridge. According to O'Hara, the lavas are derived from a unique and homogeneous mantle at the upper mantle-transition zone boundary and not, as I prefer[2], from two distinct mantle sources, one forcefully rising as a primary hot mantle plume (PHMP) beneath Iceland and interacting with the depleted low velocity layer (DLVL).

I answer each of these points in order, concentrating primarily on the rare earth (RE) data which I emphasized[2], and omitting petrological and isotopic arguments, which will be discussed elsewhere.

Also, several of O'Hara's comments concerning rare earth fractionation are, unfortunately, wrong. For example: (i) Fractional crystallization of clinopyroxene does not deplete but rather enriches a residual melt in lighter rare earths, as is evident from equilibrium partition coefficient data[3-5]. (ii) There is no relative Y enrichment towards Iceland, because I did not report nor analyse this element, and my expectation is that it will remain relatively constant, similarly to the heavy rare earths of similar ionic size, such as Er. (iii) There is no massive relative and even absolute depletion of Yb as stated by O'Hara to support his eclogite-fractionation model. The Yb abundance remains relatively constant along the ridge up to Iceland (Fig. 1a). Much of the Yb scatter is in fact analytical, as with the instrumental neutron activation method used the counting statistics are relatively poor for Yb ($\sigma_{Yb} = 15\%$, $\sigma_{La} = 9\%$, and $\sigma_{Sm} = 2.5\%$). (iv) O'Hara's use of the $[La/Yb]_{EF}$ is misleading since it bypasses the behaviour of intermediate rare earths. This ratio does not adequately contrast the behaviour of the light rare earths relative to the heavy rare earth subgrouping. All the information contained in the rare earth pattern needs to be included to constrain the models.

(1) "Primary magmas". This is a semantics problem. I have used the adjective "primary" on two occasions to indicate a temporal sequence, where by prior mixing along the transition zone, both PHMP-derived and DLVL-derived melt types are referred as "primary" in contrast to the secondary hybrid lavas resulting from mixing. I did not mean to imply that any of the lavas reported in my paper did not suffer any fractionation prior to eruption, and thus be "primary" in O'Hara's sense. In fact I clearly stated that they are porphyritic in texture, and explained plausible mechanisms by which lavas, once segregated from the residual mantle phases after partial melting during diapiric rise, would accumulate in magma chambers at very shallow depth beneath the thin oceanic crust, cool and begin to fractionally crystallize in order to produce the observed phenocrysts, as well as mix.

Elsewhere[6] I also used for synonyms[7] to "primary" the words "principal" melt types, "end-member" melt types, in referring to both PHMP-derived and DLVL-derived tholeiites.

Although we apparently agree that most of these lavas have suffered some crystallization prior to eruption, the question remaining in dispute, I believe, is quantitatively: to what extent are these melts residual, and from what mantle source or sources were they originally derived?

(2) "Olivine-gabbro and eclogite fractionation". I have shown on a $[Yb]_{EF}/[La/Sm]_{EF}$ diagram[2] the difficulty of bridging by
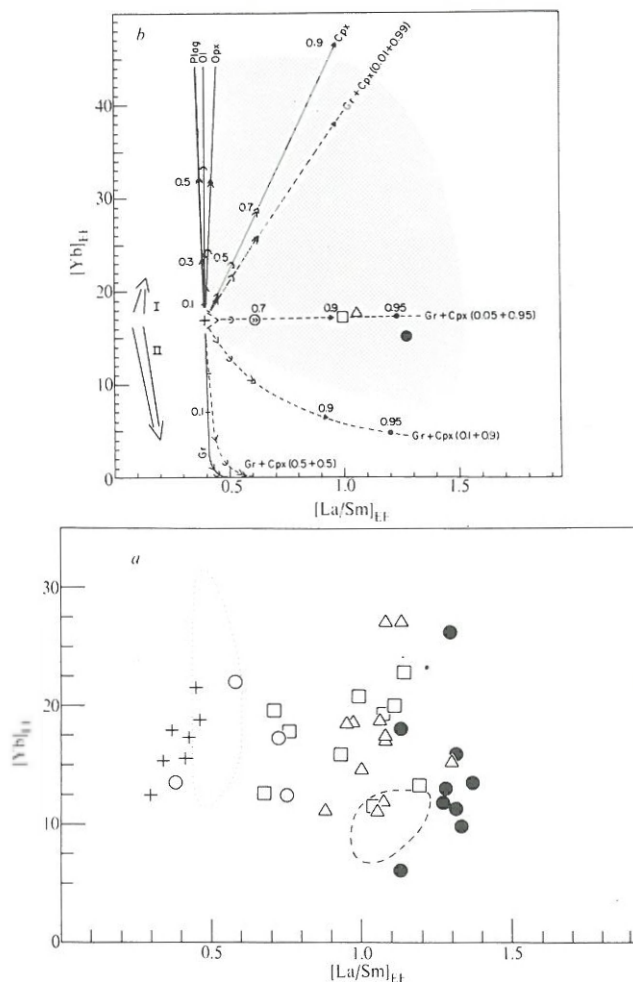

Fig. 1 *a*, Yb against La/Sm enrichment factors relative to chondritic meteorites[2] in tholeiitic basalts erupted along the postglacial Reykjanes Ridge Axis and its extension over the Middle Neovolcanic Zone of Iceland[2]. +, South of 61°N; ○, 61–62°N; □, 62–63°N; □, 63°N to Iceland; ●, Iceland. Dotted area is field of DLVL-derived tholeiitic basalts from other Mid-Ocean Ridges[8]; and dashed area is field for Hawaiian tholeiites[3]. *b*, Same diagram as above, showing theoretical control liquid lines of descent for fractional crystallization of plagioclase feldspar (Plag), orthopyroxene (Opx), olivine (Ol), clinopyroxene (Cpx) and garnet (Gr). The bar, arrow, half circle, double arrow, filled triangle and point along liquid control lines represent residual liquid composition after fractional crystallisation of respectively 10, 30, 50, 70, 90 and 95 weight % of the corresponding mineral (or bimineralic mixtures for eclogite fractionation—shown as dashed liquid control lines). The large symbols are as given in *a* for the observed values in basalts erupted along the Reykjanes Ridge, but averaged for every degree of latitude. Large arrows: I, the approximate direction of olivine-gabbro fractionation; II, of eclogite fractionation. The lengths are very roughly proportional to the rate of enrichment or depletion for a given degree of fractional crystallisation. Various paths to bridge DLVL-derived melts (+) to PHMP-derived melts (●) can be designed. All these paths require a very unusually large extent of fractional crystallisation of clinopyroxene, and cannot at the same time satisfy the major element chemistry of these two end-member tholeiites (which relative to trace elements represent only small variations). The shaded area takes into account the known range of partition coefficients[4,8] for plagioclase, and the dotted area for the clinopyroxene.

fractional crystallization melts with light RE-depleted pattern (typically mid-ocean ridge basalts, or Reykjanes Ridge south of 61°N) to melts with light RE-enriched pattern (typically island tholeiites, as Iceland), while at the same time keeping $[Yb]_{EF}$ relatively constant. This is shown in Fig. 1a and b. Only very large amounts of extraction (greater than 90%) of clinopyroxene with rather restricted partition coefficient values (and

for that matter also of bulk chemistry) could perhaps bridge both types. This is because operative RE partition coefficients for orthopyroxene, olivine and plagioclase feldspar upon fractional crystallization do not change appreciably the $[La/Sm]_{EF}$ of residual liquids, but merely increase the overall absolute RE abundances (see also Figs 13. 15 of ref. 8). Only clinopyroxene is able significantly to fractionate and enrich residual melts in the light RE. On a $[La/Sm]_{EF}/[Yb]_{EF}$ diagram (Fig. 1b) the olivine-gabbro liquid-control fractionation line would have to be intermediate between individual controlling lines for plagioclase, olivine and clinopyroxene, and its exact position would depend on the relative proportions of these minerals simultaneously being extracted at the cotectic (see arrow I in Fig. 1b). It is clear (Fig. 1b) that increasing olivine-gabbro fractionation toward Iceland cannot satisfactorily produce the observed $[La/Sm]_{EF}/[Yb]_{EF}$ variation along the ridge. This, therefore, eliminates one of O'Hara's contentions, that is, an increasing olivine-gabbro fractionation toward Iceland could produce the observed increase of the $[La/Sm]_{EF}$.

So the low pressure olivine-gabbro fractionation can only increase the scatter of $[La/Sm]_{EF}$ towards Iceland, and should be inferred only as a second order effect, as is the eclogite fractionation effect which I now discuss.

Hitherto, I had avoided consideration of the effect of garnet fractionation (although aware of its effect in depleting the heavy rare earths in residual melts having fractionally crystallized garnet[9]) because of the lack of reliable garnet-melt partition data relevant to basalt genesis under eclogitic conditions. In view of O'Hara's remarks, it is necessary to illustrate the control line of liquid descent for eclogite fractionation, using Philpotts's best estimate[10] set of RE partition coefficients for garnet, from the Kakanui region. This set of RE partition coefficient values for garnet gives consistent results with other estimates from other eclogites or garnet peridotites[10]. The set is also close to an estimate I had independently made and which is conservative on its effect in depleting the heavy RE. The effect of fractionally crystallizing garnet alone is to deplete drastically the melt in heavy rare earths such as Yb, without changing the $[La/Sm]_{EF}$ appreciably (see Fig. 1b). The garnet effect of lowering the $[Yb]_{EF}$ dominates also if garnet and clinopyroxene simultaneously fractionally crystallized from the melt as a 50–50% mixture as required by O'Hara's eclogite fractionation model[11]. Again, and contrary to O'Hara's belief, there is no way to match the observed rare earth variation along the Reykjanes Ridge with such an eclogitic fractional crystallization scheme.

Only a mixture composed of 95% clinopyroxene and 5% pyrope garnet could possibly bridge the rare earth pattern variation, but would require some 95% extract of such an unusual mixture. This is of course unacceptable, because the residual liquid of such an extract would have a major element chemistry quite distinct from an olivine tholeiite (the most common lava type over the Reykjanes Peninsula). It would also create a serious volume problem over and above having to explain the two to four times larger flux production of melt in the Iceland Region relative to more normal ridge segments, judging from crustal thickness[2].

(3) "Extent of fractionation". Although it is true that there is a tendency for increasing fractionation for lava ascending through thicker crust (or altitude), it is untenable that the general trace element geochemical trend observed along the ridge can be accounted for by increasing fractional crystallization alone. As previously noted on the $[La/Sm]_{EF}/[Yb]_{EF}$ diagram, the effect merely increases diversity and scatter about the general trend but cannot be responsible for it. Although at a first glance it may seem that altitude can be correlated with fractionation (such as reflected by the $[La/Sm]_{EF}$), a simple plot of relevant data would show that it is not a regular and simple function. A corollary of my plume model would be that basalt erupted south of 60°N be DLVL-derived and remain light RE-depleted, even though water depth continues generally to increase along the ridge axis. A series of five new rock analyses for stations spaced from 60°N up to the Charlie Gibbs Fracture Zone (~53°N) shows a constant level for the $[La/Sm]_{EF}$ just as south of 61°N (ref. 2, Fig. 3); and therefore further corroborates my model for two mantle sources of different densities and differentiation history.

O'Hara's preferred model of a single mantle source at the upper mantle-transition zone boundary[1,12] offers little substance for discussion here, as it does not take into consideration the many geophysical-geochemical and geological features which contrast Iceland with the Mid-Atlantic Ridge. I do wish to emphasise that any alternative to my model should also satisfy these many model requirements, which I have listed and have taken into consideration in my model[2].

Contrary to O'Hara's belief, I rejected the model of a single mantle source with increasing degree of fractional crystallization toward Iceland not only on the basis of isotopic ratios (evidence which for two mantle sources is overwhelming[13]), but also from rare earth considerations as outlined above and which I had to omit in my original discussion[2] for the sake of brevity.

J.-G. SCHILLING

Graduate School of Oceanography,
University of Rhode Island,
Kingston, RI 02881

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