

Discussion of

ΔNb and the role of magma mixing at the East Pacific Rise and Iceland

by

James H. Natland

25th January 2007, J. Godfrey Fitton

The Iceland melting anomaly is widely held to be the product of hot and fertile mantle supplied by a mantle plume. Recycled subducted ocean crust, for which the ΔNb parameter (Fitton et al., 1997; this volume) is intended as a proxy, provides a plausible fertile component. In a radical alternative hypothesis, Natland (this volume) proposes that melting of lithologies originating in detached or delaminated *continental lithospheric mantle and lower crust* can provide virtually the whole spectrum of Icelandic magmas. Specifically, he recognises four distinct magma types in and around Iceland:

1. Depleted basalt erupted on the Reykjanes and Kolbeinsey Ridges (south and north of Iceland, respectively) is produced by melting subcontinental lithospheric mantle,
2. Depleted Icelandic picrite results from the melting of depleted olivine gabbro,
3. Evolved Fe-Ti-rich ferrobasalt and icelandite result from the melting of oxide-rich gabbro, and
4. Rhyolite magma is produced by melting silicic veins in the gabbro protolith of magma types 2 and 3.

In Natland's model, all Icelandic magmas are the product of mixing between these four end members, and fractional crystallisation plays only a minor role in their evolution. The model is based principally on four questionable assertions.

1. The array of Icelandic data used by Fitton et al. (1997) to define ΔNb only appears to be linear because evolved rocks have been excluded. Adding intermediate and silicic compositions emphasises the curvature in a mixing array between depleted basalt and the Fe-Ti-rich or silicic end members. Figure 1 shows a second-order regression line fitted to the data used by Fitton et al. (1997). The line is almost straight and parallel to the $\Delta\text{Nb}=0$ reference line. Linear regression gives a virtually identical line with an equally good fit ($r^2 = 0.929$ for both). There is therefore no statistically significant curvature in the data array.
2. Mixing primitive depleted basalt ($\Delta\text{Nb}<0$) with as little as 1-2% of evolved andesite or rhyolite is sufficient to change ΔNb from negative to positive. A judicious choice of end members is required to make this work. Figure 1 shows Natland's mixing line between primitive "Icelandic" and silicic end members. The primitive end member has 0.3 ppm Nb and 21.9 ppm Zr, implying a source that is much more depleted than the source of normal mid-ocean ridge basalt, and yet is capable of melting at normal temperatures to supply >90% of the mass of Iceland (Figure 1). The silicic end member is a trachyte (not andesite as stated

by Natland) from the off-axis mildly alkaline Snæfellsnes volcano. It contains 122 ppm Nb and 623 ppm Zr, and is a very unlikely rock type to expect in significant amounts in the lower continental crust. Mixing between the two end members gives a very poor fit to the data of Fitton et al. (1997). Natland acknowledges this by assigning a different origin (melting of olivine gabbro) to depleted Icelandic picrite (those rocks with Zr/Y < 1.8 on Figure 1). Mixing between the primitive end member and average continental crust is incapable of reproducing the composition of Icelandic basalt (Figure 1).

3. ΔNb is insensitive to fractional crystallisation and therefore basaltic magma with $\Delta\text{Nb} > 0$ cannot be parental to Icelandic rhyolite with $\Delta\text{Nb} < 0$. This is simply not so, as can easily be shown from the Rayleigh fractionation equation,

$$C_L/C_0 = F^{D-1}$$

where C_L is the concentration of a trace element in an evolving liquid, C_0 its initial concentration, F the fraction of liquid remaining, and D the bulk distribution coefficient. Applying this equation to Nb, Zr and Y gives three equations that can be combined and rearranged to show that

$$(\log (\text{Nb}/\text{Y})_L - \log (\text{Nb}/\text{Y})_0) / (\log (\text{Zr}/\text{Y})_L - \log (\text{Zr}/\text{Y})_0) = (D_{\text{Nb}} - D_{\text{Y}}) / (D_{\text{Zr}} - D_{\text{Y}})$$

The form of this equation shows that any fractional crystallisation path on a plot of $\log (\text{Nb}/\text{Y})$ vs. $\log (\text{Zr}/\text{Y})$ will be a straight line with a slope of $(D_{\text{Nb}} - D_{\text{Y}}) / (D_{\text{Zr}} - D_{\text{Y}})$. Since $D_{\text{Nb}} \approx 0$ for most low-pressure mineral assemblages, the fractional crystallisation path will have a shallower slope than the $\Delta\text{Nb} = 0$ reference line (1.92) when $D_{\text{Zr}}/D_{\text{Y}} < \sim 0.5$ and will have a slope of unity (constant Nb/Zr) when $D_{\text{Zr}}/D_{\text{Y}} = 0$. Thus, fractional crystallisation of any assemblage in which Y is more than twice as compatible as Zr will result in a reduction of ΔNb in the evolved magma. The large arrow on Figure 1 represents 80% fractional crystallisation ($F=0.2$) of an assemblage in which $D_{\text{Nb}} = 0$, $D_{\text{Zr}} = 0.13$ and $D_{\text{Y}} = 0.96$, equivalent to a mixture of 40% clinopyroxene (D_{Zr} and D_{Y} from Ewart and Griffin, 1994) and 60% of phases (e.g. feldspars) in which all three elements have $D=0$. Fractional crystallisation of clinopyroxene-bearing assemblages can readily account for the negative values of ΔNb found in some Icelandic rhyolites. Clinopyroxene joins the low-pressure crystallising assemblage at ~ 5 wt.% MgO in Icelandic tholeiites, which is why Fitton et al. (1997) excluded basalt samples with < 5 wt.% MgO. Partial melting of hydrated basaltic crust (amphibolite) is also likely to produce rhyolite with $\Delta\text{Nb} < 0$ because amphiboles in equilibrium with silicic magmas also have $D_{\text{Y}} \gg D_{\text{Zr}}$ (Ewart and Griffin, 1994).

4. A tenfold range in TiO_2 contents in parental Icelandic basalts cannot be explained by partial melting of peridotite. This is valid only if magmas are produced by equilibrium melting of a homogeneous mantle source. Titanium is only moderately incompatible in mantle phases and so a tenfold abundance variation in primary melt would require more than a tenfold variation in degree of melting. But melting is not an equilibrium process, and radiogenic-isotope ratios show that the source cannot be homogeneous. Fractional melting of a heterogeneous mantle source will strip out the more fusible and Ti-rich material first, leaving a progressively more Ti-depleted peridotite residue to contribute during advanced stages of melting. These two extremes are represented in Iceland by, respectively, small volumes of enriched off-axis basalt (e.g. Snæfellsnes) and even smaller volumes of depleted picrite erupted in the rift axes (Hardarson and Fitton, 1997; Fitton et al., 2003). Most on-axis melting, however, will produce melt that reflects the bulk composition of the mantle, and this melt will evolve by

fractional crystallisation to produce the ubiquitous Icelandic tholeiite (Figure 1). Natland's model implicitly appeals to fractional melting but his source is a mixture of depleted olivine gabbro and enriched ferrogabbro, both derived from the lower continental crust.

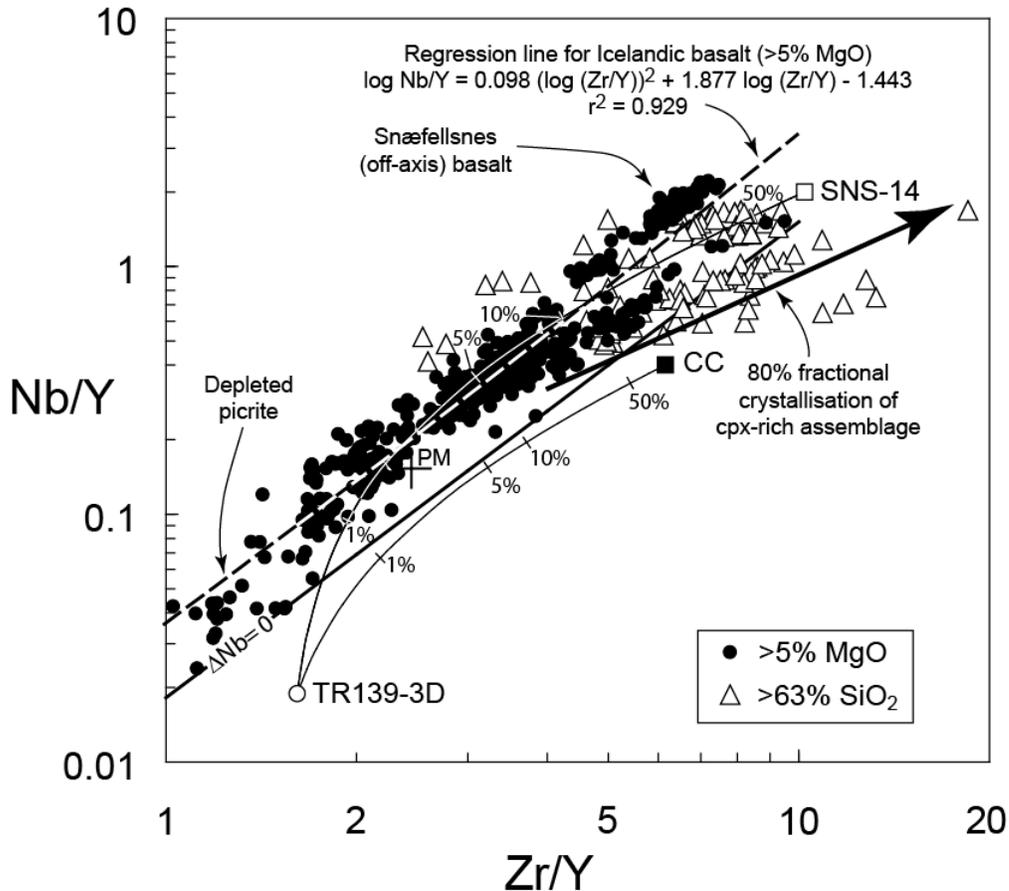


Figure 1. The composition of Icelandic basic (Fitton et al., 1997) and silicic (GeoRoc) volcanic rocks compared with average continental crust (CC, from Rudnick and Fountain, 1995 and Barth et al., 2000), and primitive mantle (PM, from McDonough and Sun, 1995). Basic volcanic rocks (>5 wt.% MgO) form a linear array parallel to the $\Delta\text{Nb}=0$ reference line (from Fitton et al., 1997). Mixing lines between the depleted (TR139-3D) and enriched (SNS-14; wrongly identified as SNS-17 in GeoRoc) end members proposed by Natland, and between the depleted end member and average continental crust are also shown. The large arrow shows that the silicic rocks could be derived by fractional crystallisation from average Icelandic basalt.

The foundations of Natland's model are unsound. He invokes an *ad hoc* assemblage of lithologies inferred to exist as major components of the lower continental crust, and for which there is little evidence. These lithologies were transferred to the convecting upper mantle during continental break-up and provide a constant source of tholeiitic magmatism that has lasted for >55 Ma and shows no sign of exhaustion. By contrast, the plume model for Icelandic magmatism requires only two lithologies – variably depleted peridotite and an enriched component that could

be eclogite. This assemblage is known to be fed back into the upper mantle through subduction, and its recycling through a mantle plume provides a plausible and virtually inexhaustible supply of mantle that is both fertile and hot. It can explain all the first-order geochemical features of Iceland with far fewer and more plausible assumptions and postulated components than Natland requires. Natland's hypothesis would not survive the application of Occam's razor.

I thank the Editors for special permission to post a slightly longer comment than normally allowed.

2nd February 2007, James H. Natland

Fitton's sense is that I have advocated a random set of end-members just to suit my model (see his comment of 25th January). No. They all go together, as they do in Nature. We must stop thinking that each source lithology exists in physical isolation, in reservoirs. They never do. In this case, there's good reason for them to be together, and this allows a new, unifying, simplifying, and far from *ad hoc* hypothesis for Icelandic petrogenesis. The key is that the ONE source (call it the lower continental-crust assemblage) is polyolithologic. This is far from arbitrary, just common sense, and simple.

I stated from the start that the Iceland trend was flatter than for MORB; I never tried to explain negative ΔNb in rhyolite by crystallization differentiation. Fitton offered enriched eclogite as the source of high-Ti basalt, which was one of the main points of my paper. In addition, his attempt to explain rhyolite doesn't make rhyolite.

1) Fitton's linear regression only makes the flat trend for Iceland even more explicit. The flat trend is largely because of the low-Ti olivine tholeiites and picrites derived, as I argue, from olivine gabbro cumulates or equivalent eclogite. Curvature on a ΔNb diagram within data for basalt is evident especially for the northern part of the eastern rift. The curve partially overlaps the data from Kolbeinsey Ridge (KR) just to the north, which includes samples with negative ΔNb . The depleted sample I used for my calculation is from a submerged portion of the Iceland platform abutting the Tjörnes Fracture Zone, which offsets Iceland from the KR, suggesting that the depleted peridotite source for the KR extends some distance beneath northern Iceland.

2) Fitton notes that the "andesite" from Snaefellsness is actually a trachyte; this was an error in GeoRoc. It hardly matters. Other andesites, dacites, or rhyolites could be used to make the same point. Fitton worries about the temperature of melting of the source of the primitive mixing component. Extent of depletion has nothing to do with melting temperature. Low-Ti basaltic melt can be produced by partial melting of refractory, near-harzburgitic peridotite at the same temperature and nearly to the same extent as basalt from fertile lherzolite (Jaques and Green, 1980; Natland, 1989; Presnall et al., 2002). I did not say and do not know what percentage of Iceland is derived from such a melt type or its differentiated residua. I suggested that partial melting of eclogite transformed from depleted olivine-gabbro and oxide-gabbro cumulates is

responsible for most of Iceland. Eclogite has a lower melting temperature than peridotite (Anderson, 2005; Foulger et al., 2005).

3) I did not discuss derivation of rhyolite with negative ΔNb . I am concerned mainly with trends among basalts and how they might be influenced by silicic contamination or mixing. Fitton's scheme would not make rhyolite. It cannot increase SiO_2 nor reduce FeO and TiO_2 from amounts in the starting basalt. It has to involve oxide minerals, which have higher partition coefficients for Nb and Zr than for Y (compilation of Bédard, 1994). The question is not whether Icelandic rhyolite is derived from some basalt by crystallization differentiation, but whether it is derived in this way from Icelandic tholeiite today. Any of it with higher $^{87}\text{Sr}/^{86}\text{Sr}$, which is most of it, cannot be; on this basis, no rhyolite at Iceland is related by crystallization differentiation to primitive olivine tholeiite and picrite. Plenty of rhyolite in the Deccan and Karoo flood basalt provinces has negative ΔNb but it has even more obviously continental isotopic signatures. It is derived by partial melting of granitoids, granulites, or amphibolites that were produced by crystallization differentiation of basalt, metamorphism and partial melting of metabasite through long geological time (Betton, 1979; Hawkesworth et al., 1984; Mahoney, 1988; Bédard, 2006). These plot at the same location as Icelandic rhyolite on a ΔNb diagram, but they are clearly not derived from Mesozoic flood basalt by crystallization differentiation. Iceland is a geochemically feebler version of this, and of associations in Greenland and Scotland. Along the East Pacific Rise, crystallization differentiation of primitive basalt does not significantly change Nb/Y or Zr/Y and thus ΔNb . The same should be true even if the parental basalt has positive ΔNb . At Iceland, therefore, why is there such a spread in these parameters just among basalts with $> 5\%$ MgO? It can't be done by crystallization differentiation, but it can be by mixing with rhyolite, andesite, or rhyolite-contaminated ferrobasalt, even if it is produced along the lines of Fitton's model. Remember also that $^{87}\text{Sr}/^{86}\text{Sr}$ increases generally to the right on a ΔNb diagram among Icelandic basalts.

4) Partial melting of commonly construed mantle peridotite does not produce high-Ti basalt. This fails utterly to explain absence of any kind of trends and the high Ti_8 of many Icelandic tholeiites. Fitton can argue in terms of partition coefficients and fractional melting, but a far simpler explanation is to allow the presence of a titanian phase in the source, which likely means that it is (was) gabbroic. Since in the end Fitton does suggest eclogite for the "enriched component", why not regard it as a facies (rather than high-pressure average MORB) and include among its precursors oxide gabbro with a titanian phase? Oxide gabbro will almost certainly accompany any body of olivine gabbro adcumulates in the protolith.

Fitton's initial and final comments concern the four-fold diversity of lithologies I invoke as sources for Iceland and adjacent ridges, which he terms an assemblage so *ad hoc* that it "would not survive the application of Occam's Razor." I emphasize that in the lower continental crust, where I believe three of the four originate, they occur together and will stay together should portions of lower continental crust sink into subcontinental mantle (the fourth). Accepting that tholeiitic high-iron differentiation characterizes many layered intrusions, olivine gabbro cumulates and oxide gabbros will be present together in plutonic assemblages in the continental crust wherever such differentiation has taken place. A lot of it did take place to make, e.g.,

ancient granitoids (Bédard, 2006), Bushveld felsites, Phanerozoic island arcs etc. Later remelting of such composite assemblages would produce parallel strains of quite different partial melts. This is the simplest explanation for the duality of Icelandic basalt and much of the mixing I infer. Also, Icelandic rhyolite need not come simply from partial melting of gabbro; other lithologies might be involved, and their melting or assimilation would result in high Nb/Y and Zr/Y with positive ΔNb . Thus during foundering of deep gabbroic constituents of continental crust, something granitic (granitoidal, gneissic, migmatitic, granulitic) may descend as well, all the rocks sinking into refractory, often harzburgitic, subcontinental lithosphere. Basalts from Reykjanes and Kolbeinsey Ridges have the least Ti_8 and Na_8 of all MORB, and recent interpretation is that this is not so much a consequence of high temperature, but of a refractory, more nearly harzburgitic, source (Natland, 1989; Presnall et al., 2002). Where do we KNOW such refractory lithosphere occurs in abundance? Why, beneath the continents! Following rifting, all source lithologies are unavoidably involved in rift-related partial melting. This is why similar low-Ti basalt occurs near the Seychelles micro-continent in the Indian Ocean (Natland, 1991).

The gentle dispensation of the editors allowed me to match the length of Fitton's discussion. Many thanks.

4th February 2007, J. Godfrey Fitton

Placing the four postulated end-member protoliths for Icelandic basalt in close proximity in the lower continental crust and lithospheric mantle doesn't make them any less *ad hoc*. They still need to be conveniently similar in composition to Icelandic basalt. Lower continental crust is mafic in composition (Rudnick and Fountain, 1995), but there the similarity to Icelandic basalt ends. Icelandic basalt and lower continental crust differ in two crucial respects. First, crustal rocks tend to be deficient in Nb (e.g. low Nb/La and negative ΔNb) whereas Icelandic basalts have higher Nb/La (Hémond et al., 1993) and positive ΔNb . Natland requires at least one component with a high concentration of Nb and strongly positive ΔNb . Second, Icelandic basalt and ancient lower crustal rocks have very different Sr-Nd-Pb-isotope ratios. This is evident from the extreme isotopic composition of the earliest (61 Ma) basalts erupted on the south-east Greenland continental margin before the opening of the North Atlantic Ocean (Fitton et al., 2000). The lower crustal granulites with which these are inferred to have been contaminated cannot be a significant component in the source of modern Icelandic basalt.

Natland proposes that his assemblage of lower continental crust and lithospheric mantle lithologies became detached and incorporated into the convecting upper mantle during the rifting episode that led to the formation of the North Atlantic Ocean. How much time is required for this assemblage to warm up enough to produce basaltic melt on decompression? Excess magmatism in the region would be expected to postdate continental separation at 55–54 Ma, but this is not so. Large-volume tholeiitic magmatism started synchronously across a 2000-km-wide area stretching from Baffin Island, through Greenland, to Scotland at around 61 Ma (Saunders et al., 1997). The sudden, widespread onset of magmatism before continental separation is predicted by the plume hypothesis but is difficult to reconcile with Natland's alternative model.

6th February 2007, James H. Natland

I invoked gabbro/eclogite, not granulite, as a source for Icelandic basalt. Granulite and felsic xenoliths (Rudnick and Fountain, 1995) are similar to Icelandic rhyolite with negative ΔNb on a ΔNb diagram (round symbols, Figure 2); the felsic rocks have $>70\%$ SiO_2 . Other symbols are Canadian Archaean and Proterozoic gabbros (Owens and Dymek, 1992; Li et al., 2000; Leatherdale et al., 2003; Kerr, 2003). Eight of these are oxide-apatite gabbronorites with high TiO_2 (4.6-10.6%), total iron as Fe_2O_3 (19.7-41.6%) and P_2O_5 (2.8-5.4%) contents; they are ilmenite-magnetite-apatite cumulates. Others are mainly leucogabbro with low oxide contents. Most of the gabbros have positive ΔNb ; the others overlap felsic xenoliths. The entire suite resembles enriched Icelandic high-Ti basalt and rhyolite in ΔNb . The gabbros have other suitable attributes (high Sr and Ba, and steep REE patterns). On this basis, I see no reason to abandon my hypothesis that gabbroic material, particularly oxide gabbro, and something silicic (granitoid, gneissic, migmatitic, granulitic) from the lower continental crust, left by foundering in the mantle during rifting, comprise the source of high-Ti Icelandic basalts.

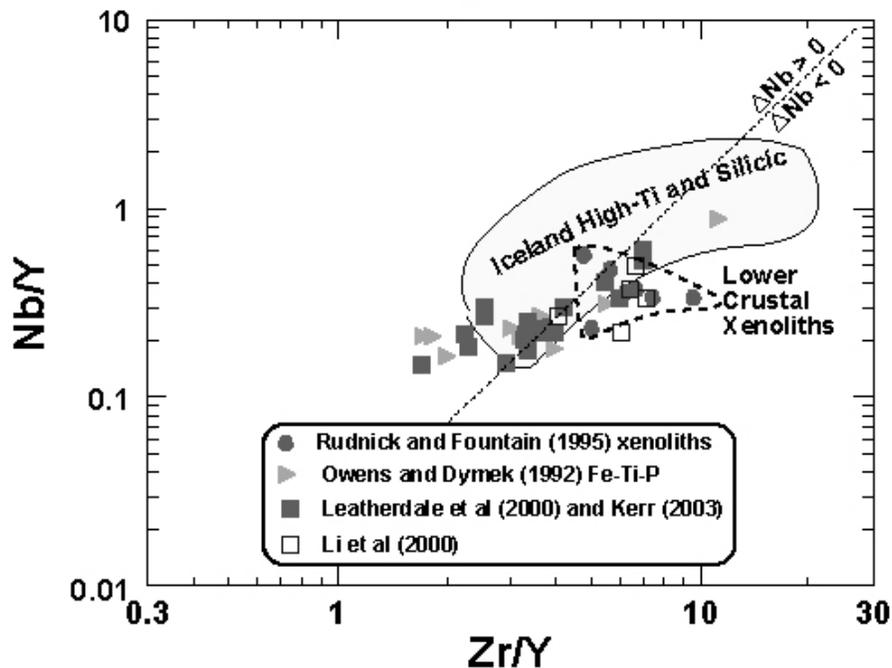


Figure 2

I accept the more general point that it is early in the game to accept without reservation continental or subcontinental sources for Iceland; we do not yet have a full assessment of lithologies in those sources, their geochemical variability, or the mechanisms by which they attained that variability (crystallization, anatexis, melting of amphibolite etc.). We do not fully understand partitioning of trace elements like Nb and Ta during metamorphism to eclogite, or

into liquids during partial melting of eclogite (e.g., Barth et al., 2000; Rudnick et al., 2000). I am not particularly concerned with the somewhat high La/Nb of granulite xenoliths and most of the gabbros compared with Icelandic basalt (they actually partially overlap). This is a slight dissimilarity amidst strong similarities. Misfit isotopic ratios in Eocene basalt from a locality in Greenland only means that the Iceland source is now different; granulites and continental gabbros can be depleted or enriched. How a feebly enriched but originally continental source came to remain under Iceland is still conjectural. Obviously, a granitic crust had a stronger influence on basalt compositions in Greenland and Scotland than it does at Iceland now; most of the granite has been removed. The province is smaller now, as it should be.

Jull & Kelemen (2001) summarize evidence that gabbro and pyroxenite produced in the differentiation of island arcs are NOT abundant in deep sections of the crust; this is why they argue that such rocks founder into the deeper mantle. Gabbros *sensu stricto* are also not among the xenolith types in Rudnick and Fountain (1995), although some may be included in their average mafic granulites.

Daly (1926, 1933) invoked foundering of the roots of mountains to explain their elevation, and pointed out that the earliest proto-continental crust no longer exists; it foundered back into the Earth's interior. This foundering of lower crust continues. How can we ignore these potential sources for modern volcanic suites? Why suppose that all unusual compositions are tied up in plumes? We have become used to viewing subduction as the only mechanism for introducing heterogeneity into the mantle, and plumes as the only mechanism for retrieving it. Neither mountain building nor continental drift has ever been a clean process. Drifting continents produce plenty of flotsam and jetsam in their wake. This is the minimal conclusion that geochemists are starting to draw in all the discussion about delamination leaving its geochemical signature on ridge basalts in the Indian Ocean. The serious question is how large the scale of this might be. The distributions of radioactive heat, fusible material, and structural weakness in continents are not uniform. The process of manufacture of continental crust is very uneven, which is why rifting is favoured where places are still warm, weak and refulgent with easy-to-melt materials. This is also why, after continents drift away, some magmatic provinces in ocean basins, like Iceland, are bigger than others.

I thank Godfrey Fitton for his efforts first at reviewing my paper, and then offering comments that compelled me to expand and clarify my arguments. We may not agree, but our discourse through these and many private communications has always been friendly, courteous, informative, and very valuable.

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