ΔNb and the Role of Magma Mixing
at the The East Pacific Rise and Iceland

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"It is an old idea that the more pointedly and logically we formulate a thesis, the more irresistibly it cries out for its antithesis."

- Hermann Hesse, 1943, *Das Glasperlenspiel,* translated in 1969 as *The Glass Bead Game* by Richard and Clara Winston

ABSTRACT

ΔNb is a geochemical construct of Fitton et al (1997) based on two trace-element ratios, Nb/Y and Zr/Y, plotted against one another on a log-log diagram. ΔNb is defined in relation to a diagonal line on the diagram separating Nb-enriched Icelandic tholeiite from Nb-depleted mid-ocean ridge basalt (MORB). Neither crystallization differentiation nor partial melting of a peridotite mantle source can drive compositions below the line, with negative ΔNb, to locations above the line, with positive ΔNb, or vice versa. The parameter ΔNb thus is taken to indicate distinct mantle sources.

Crystallization differentiation along the East Pacific Rise has almost no effect on ΔNb. The low and similar partition coefficients for Y, Zr, and Nb during shallow crystallization differentiation ensure that data points for primitive and evolved basalt as well as rare iron-enriched andesite and dacite plot virtually atop one another on the diagram, with all differentiates retaining negative ΔNb. Only enriched (E-)MORB obtained both from ridge segments and the summits of some near-ridge seamounts, and which in the extreme includes alkalic olivine basalt, has positive ΔNb. N-MORB and E-MORB together produce a curving array that crosses the line on the diagram, and this crossing trend indicates heterogeneity in the source.

At Iceland, on the other hand, tholeiitic ferrobasalt and abundant andesite, dacite and rhyolite are widely separated from primitive basalt on such a diagram, plotting at successively higher Nb/Y and Zr/Y at positive ΔNb. The most enriched rocks at Iceland are rhyolites with approximately the geochemistry of the inferred common mantle component, FOZO. The rocks cannot be related to each other either by crystallization differentiation or partial melting of a peridotite source. Calculations show that mixing of only 1-2% rhyolite or ~5% of evolved basalt with primitive basalt can shift Nb/Y, Zr/Y and in certain circumstances ΔNb to higher values; it can also shift chondrite-normalized

patterns of rare-earth elements (REE) in primitive basalt from negative to positive slopes, a general attribute of Icelandic lava suites, and the progression along Reykjanes Ridge approaching Iceland from the south. Both isotopic ratios and other trace-element concentrations and ratios are consistent with such mixing.

At Iceland, the usual differentiated and enriched mixing component is ferrobasalt with TiO_2 contents so high that it cannot be derived from commonly construed mantle peridotite; a Ti phase such as ilmenite, titanomagnetite or – at high pressure – rutile, must be in the source. Most picrites, on the other hand, have lower amounts of Nb, Y, Zr and TiO_2 than primitive MORB. These attributes have led previous workers to propose a source in recycled ocean crust for both types of basalt, brought to the vicinity of Iceland in a mantle plume.

Given the generally enriched character of all Icelandic basalt and the association with rhyolite, however, I suggest instead that they all are linked to a common source and that they represent successive fractional melts of gabbroic cumulates originally produced during differentiation of ancient granitic continental crust. Much later, during the early stages of the current rifting episode in the North Atlantic, the dense gabbro sank into the warming upper mantle by means of convective instability, converting to eclogite. As Greenland separated from Europe, the eclogite experienced decompression partial melting that contributed to eruption of flood basalt, and some of it is retained in the Iceland melt source to this day. High ΔNb of basalt at Iceland thus is less an indication of mantle source heterogeneity than it is for mixing between depleted basalt and petrogenetically unrelated mafic to silicic differentiates having an ultimate origin in ancient continental crust. It is not evidence for the existence of a mantle plume.

INTRODUCTION

ΔNb was invented by Fitton et al. (1997) to provide a clear-cut discriminant between mid-ocean-ridge basalt (MORB) and Icelandic tholeiite, with potential application to other places (Baksi, 2001; Fitton, this volume). It is based on two trace-element ratios, Nb/Y and Zr/Y, when plotted against one another on a log-log diagram, which can be called the ΔNb diagram. My attempts to utilize it to interpret several flood-basalt provinces raise problems of both definition and interpretation. Briefly, these stem from: 1) restricting the perspective just to certain types of basalt; and 2) assuming that their geochemical signature comes strictly from peridotite, plus variable amounts of crystallization differentiation. An important difficulty turns out to be identifying the effects of magma mixing between primitive and strongly differentiated (e.g., ferrobasaltic to rhyolitic) components, or alternatively assimilation of silicic materials in the crust by basaltic magma, something that occurs commonly in flood-basalt provinces, and seeing through this to an original mantle signal. Such mixing can shift ΔNb. The boundary, ΔNb = 0, itself appears to be somewhat arbitrary, since its formulation depends on distinguishing between an array just of tholeiitic basalts (MgO > 5%) from Iceland, and depleted N-MORB (Fitton et al., 1997). Add less magnesian (including silicic) rocks to Iceland, and the full panoply of transitional and enriched (T- and E-) MORB plus some silicic rocks to depleted N-MORB from, say, the East Pacific Rise and its near-ridge seamounts or the Indian Ocean, and the picture changes.

High ionic potential (high ratios of charge, or valence, to ionic radius) means that Nb, Zr, and Y are almost insoluble in water, thus not readily removed from crystal lattices during alteration or metamorphism; their high valence (+3 to +4) also means that they require coupled substitutions with other elements to maintain charge balance during crystallization. Consequently they have very low partition coefficients for silicate minerals at the melt stage (they partition strongly into melts). Thus these elements are ideal for the study of magmatic processes, even if the rocks are substantially altered. Since they can now be measured to high precision by at least a couple of techniques, they serve better for this purpose than elements that really do move around during alteration (e.g., the monovalent large-ion lithophile elements K, Rb and Cs, and to a lesser extent,

divalent Ba). This is especially important where volcanic glass is lacking, as in most subaerial exposures, and in older provinces where alteration is likely to be significant. Potential correlations with rare-earth elements, which are also nearly immobile during alteration, and the isotopic ratios of Sr, Nd, and Pb, are important. Because of their high charge relative to radii, the elements Zr and Nb, as well as Hf and Ta, have been termed *high-field-strength* (HFS) elements and Y is usually grouped with them.

As I said, Nb, Zr, and Y strongly partition into melts during crystal-liquid separation processes, but not quite equally, and herein is their main utility. Partitioning theory can be used to establish how they should behave under particular conditions of partial melting and crystallization differentiation. If one or another of these elements, but usually Nb, doesn't conform to theory, then the anomaly, which is to say the extent of the difference between theory and fact, can be attributed to source heterogeneity. Thus ΔNb, derived from a ΔNb diagram, is a measure of one such anomaly. Fitton et al. (1997) used positive values, especially high ones, to reveal what they termed "the thermal and compositional structure of the head of the ancestral Iceland plume".

Of the three elements, Nb is most strongly partitioned into melt during shallow crystallization differentiation, Zr is next, and Y is least, principally because Y has a slightly higher partition coefficient for clinopyroxene (D = 0.467) than for the other low-pressure silicate minerals (D = 0.17 to much less; e.g., Bédard, 1994)). In essence, however, all three elements are strongly preferentially concentrated into residual liquids during shallow crystallization differentiation, thus the ratios Y/Zr and Nb/Zr do not change significantly during formation of gabbroic cumulates. That is, bulk distribution coefficients involving minerals that precipitate from basaltic magma into gabbro are extremely low for Nb and Zr, and only slightly higher for Y. The picture is somewhat different at higher pressure, inasmuch as Y partitions strongly into garnet (D = 2.8; Johnson, 1998).

Sometimes it is useful to think of the behavior of Y, Zr, and Nb in comparison to the particular rare-earth elements (REE) that behave similarly (they have similar partition coefficients), but which until recently have been far more difficult to analyze. Respective REE with similar behavior are, for Nb – the light REE, La and Ce; for Zr – Nd and Sm; and for Y – the heavy REE, Er and Yb. Thus during shallow crystallization

differentiation of a single parental MORB, all REE except Eu (which is both divalent and trivalent, thus has a high average partition coefficient for plagioclase depending on oxidation state) should increase in step on chondrite-normalized or mantle-normalized REE diagrams. Consequently, at many places in the ocean crust we can select a group of moderately to strongly differentiated depleted MORB with nearly parallel REE patterns (having a narrow range of, say, Ce/Yb), even to compositions as evolved as andesite (Figure 1A), and we should expect the HFS ratio Nb/Y not to change among these samples either (Figure 1B). On a ΔNb diagram, data points should cluster in a small region regardless of their extent of differentiation (Figure 1C).   On the other hand, if the REE patterns of the basalts vary in steepness, or there are crossing REE patterns, then we should expect significant spread of data arrays on ΔNb diagrams. This indeed is what occurs at Iceland (light blue data field in Figure 1C) and along different portions of the global system of spreading ridges (orange fields).

Thus the two ratios Nb/Y and Zr/Y respectively provide comparisons to the steepness of light/heavy and intermediate/heavy portions of REE diagrams. If we equate flat REE patterns to relative depletion, and strongly sloping REE patterns (a positive linear correlation between Nb/Y and Zr/Y on the ΔNb diagram) to relative enrichment, then Nb/Y of basalt in particular is an index of the state of enrichment of mantle sources *assuming that nothing has modified the signal imparted by partial melting in the mantle, and also assuming that the mantle itself is a single composition of peridotite.*

Formally, ΔNb is the distance above or below the sloping dotted line drawn in Figure 1C, which separates data fields for Icelandic tholeiites (light blue field) and MORB (orange fields), the latter including basalt from Reykjanes Ridge adjacent to Iceland (Fitton et al., 1997). The formula of the line is $1.94*\log(Zr/Y) = -\log(Nb/Y) - 1.74$, so that for given samples $\Delta Nb = 1.74 + \log(Nb/Y) - 1.94*\log(Zr/Y)$. Positive values are Iceland-like; negative values are MORB-like.

However, bear in mind that ΔNb diagrams compare *ratios* on a log-log diagram. This gets away from dealing with concentrations altogether when presenting the results of models. Thus Fitton et al. (1997) came up with very tight linear trends and established a compositional dichotomy between N-MORB and Icelandic tholeiite with literally no overlap. Their partial melting models (blue lines in Figure 1C), constructed assuming a

homogeneous mantle and no interactions with crustal rocks, produced nearly linear relationships for liquids and solid residues for both spinel and garnet peridotite that closely parallel the line given by their equation. Note the more pronounced effect among fractional melts in the garnet stability field (G), an indication of the high partition coefficient of Y for garnet. However, note also that this does not drive the model trend across the line for ΔNb = 0. The "goodness" of the fit was enhanced by selecting among the array of possibilities between batch melting and fractional melting the proper amount of melt (2%) retained in the melt source following each step of incremental removal of partial melt. A similar set of models could be constructed assuming lower ΔNb, and this would explain the MORB array. By partial melting, at least, the Icelandic field with higher ΔNb could not be derived from depleted MORB mantle, and source heterogeneity of trace elements is proven.

This sort of evidence for rare-earth elements provided the initial geochemical rationale for the model of a plume beneath Iceland (Shilling, 1973a). Other workers then endorsed the concept, and Fitton et al. (1997) assumed its existence in order to use ΔNb to modify the model for an Iceland plume. Bear in mind that the assumption of mantle homogeneity on which the Fitton et al. (1997) melting models are based seemingly contradicts the conclusion that the mantle is heterogeneous in trace elements. One must thus further assume that the trace elements are present in such low concentrations that they behave as ideal dilute solutions and do not influence melting relationships among principal silicate phases. For the purposes of modeling, this is certainly convenient, but it leaves unexamined the question of whether the contrast in trace elements actually does indicate a difference in compositions of phases, or even the presence of other important melting phases, either of which could affect melting relationships, and it provides no formal comparison to melting models based on major oxides.

Now, a decade later, larger and more inclusive data sets reveal that trends for the East Pacific Rise, the Reykjanes and Kolbeinsey Ridges, Iceland and other flood basalt provinces are oblique to the trends and line of Fitton et al. (1997), and that those of the flood-basalt provinces flatten at higher Zr/Y. Evidently something other than partial melting is going on. By examining the inclusive data sets, I have discovered that, at all places I have investigated in detail (Iceland, the Karoo of South Africa, and the Deccan

of India), what can be termed "end-member" mixing, between primitive and strongly differentiated magma types (viz., basalt and rhyolite), or its equivalent cast in terms of assimilation (contamination) processes, is very important, although it produces effects of different degree on ΔNb at the different places. The curvature of the trends is mimicked by simple model mixing calculations. Although such end-member mixing was already known from isotopes for the Deccan and Karoo, the more general prevalence of it even among depleted compositions along spreading ridges has not previously been shown, nor its potential consequences for interpretation of mantle geochemistry considered. Quite simply, the likelihood of basalt-rhyolite magma mixing at these places, and even mixing between certain types of basalt, compromises seriously any ability to close in on the primary mantle geochemical attributes of parental basaltic magma. The effect is least along the East Pacific Rise, larger at Iceland, and most important at the continental flood basalt provinces where basalts erupt through ancient granitic crust. In short, so-called enriched mantle signatures at these places, or similarities to E-MORB, which are often interpreted to support the mantle plume hypothesis, are instead a signature of rhyolite or other strongly differentiated melt mixed into or contaminating depleted basalt. At all these places, the petrological and geochemical problem now properly should shift from concerns about the mantle to the origin and differentiation of rhyolite and associated strongly differentiated basalt, and the mechanism of their interaction with primitive basaltic magma ascending through the crust.

In this paper, I provide the crux of the mixing argument by comparing the East Pacific Rise and Iceland. In a paper in preparation, I consider the Karoo and Deccan provinces, and the Deccan in light of subsequent volcanism along the Chagos-Laccadive Ridge and Mascarene Plateau, down to the active volcanic island, Réunion. I develop an alternative to the modern hypothesis of plume heads and tails espoused initially by Morgan (1981), Campbell and Griffiths (1990, 1993) and Griffiths and Campbell (1991) to explain these and other places. The place to begin, however, is the East Pacific Rise.

Throughout, I have used data files available in the Petrological Data Base of the Ocean Floor (PetDB; available at http://www.petdb.org) of Lamont-Doherty Earth Observatory, and Geochemistry of Rocks of the Oceans and Continents (GeoRoc; available at http://georoc.mpch-mainz.gwdg.de) of the Max Plank Institut für Chemie.

THE EAST PACIFIC RISE

About equal proportions, roughly 6% each, of silicic lava (MgO < 5% and SiO_2 = 53-67%) and E-MORB (MgO > 5%; $[K/Ti]_N$ > 0.18, including alkalic olivine basalt) have been sampled along the axis of the East Pacific Rise between Siqueiros and Clipperton Fracture Zones. Most eruptions occur along a shallow and very narrow fissured depression <1 km wide sometimes called a *neovolcanic zone* that is situated almost directly and about 1 km above a barely wider seismically detectable axial melt lens that is interpreted to be a persistent, indeed, steady-state feature that lies just beneath the base of sheeted dikes (Kent et al., 1993; Harding et al., 1993; Sinton and Detrick, 1992). From a single exposure through a partial section of fast-spread crust at Hess Deep in the eastern equatorial Pacific including high-level gabbros, the melt lens is inferred *most of the time* (between eruptions) to contain highly differentiated iron-rich basaltic magma capable of precipitating gabbronorite and oxide gabbro cumulates (Natland and Dick, 1996). The gabbros are crosscut in places by tonalite/trondhjemite veins and dikelets. These rocks are present at the top of the gabbros because the melt lens is nearest hydrothermal reaction zones in fractured basaltic crust near the base of the dikes, and thus it tends *on average* to contain the coolest, therefore most strongly differentiated magmas in the gabbroic layer.

At the eruptive stage, the dynamics of spreading at a fast-spreading ridge constrain most magma migrating from the mantle and the consolidating gabbroic layer of the crust to flow from a broad base more than 100 km wide (Melt Seismic Team, 1998) toward and through the narrow melt lens. Thus primitive to moderately differentiated magma encounters the melt lens and necessarily entrains and mixes with the cool and strongly differentiated liquids there contained (Natland and Dick, 1996). The economy of basalt along the East Pacific Rise therefore consists of three extremes: 1) depleted primitive MORB derived from the mantle; 2) enriched or E-MORB, also derived from the mantle; and 3) strongly differentiated mafic and silicic magma, the melt composition of the latter being sodic rhyolite. In every geochemical respect, the depleted basalt that we call N-MORB lies between these extremes, and its average, even after screening out E-MORB as many geochemists do, is not itself an end-component.

Because almost all melt migration paths lead to narrow melt lenses, depleted primitive MORB derived from the mantle almost never erupts above the melt lens without first mixing with some fraction of E-MORB and, at the melt lens, strongly differentiated mafic and silicic magma. Sometimes magma entry into the melt lens from the sides and below purges the strongly evolved magma from the lens and it erupts as composite basalt-andesite lava flows (Natland, 1991a). Where primitive MORB does erupt without such mixing, or at least with less such mixing, is along the floors of transform faults, on very near-ridge seamounts, and at the tips of rifts propagating within microplates (e.g., Natland, 1980; Perfit et al., 1996; Sinton et al., 1991; Allan et al., 1989; 1996; Niu et al., 2002b). These are all places where melt lenses have not been detected seismically. Basalt at such locations tends to have MgO >8% (some are picrites), to be strongly depleted in light REE (Figure 1A), to have low Nb/Y and Zr/Y, and the most negative ΔNb (Figure 1D). The great majority of depleted MORB that erupt along the neovolcanic zone have flatter REE patterns - some with negative Eu anomalies, higher Nb/Y and Zr/Y, and higher, albeit still negative, ΔNb, than much basalt from transform faults. E-MORB are enriched in light REE, but have steep REE patterns overall (Figure 1A), and they lack Eu anomalies. Most silicic lavas have approximately the composition of iron-rich andesite; they have high concentrations of REE, but still flat patterns and pronounced Eu anomalies. As already noted, these evolved rocks differ but little from typical N-MORB of the neovolcanic zones in Nb/Y, Zr/Y and ΔNb.

To distinguish the primitive and more strongly depleted basalts of transform faults and seamounts from those that erupt above melt lenses, I shall term the former "truly depleted MORB", and postulate that they are representative of depleted mantle regionally along the East Pacific Rise. "Truly depleted" means, for example, strongly negative slopes to the left-hand portion of chondrite-normalized REE (the light REE; see example in Figure 1A), but also extremely low concentrations in glasses of, e.g., K_2O (0.01-0.03 %), Ba (1-2 ppm), and Rb (0.1-0.3 ppm). N-MORB erupted above melt lenses consequently begin their existence as truly depleted MORB and they become slightly more enriched because of almost inescapable mixing with small amounts of E-MORB and evolved melt-lens magma. They are also more differentiated (lower MgO and MgNo) because of residence within the cooling lower ocean crust. Because E-MORB

exists, however, the extent of magma mixing between enriched and truly depleted magmas must be variable, even allowing fairly strongly enriched alkalic olivine basalt to erupt some of the time along or very close to the ridge axis (Batiza et al., 1977; Natland and Melson, 1980). Based on the statistics of rock compositions, the mantle consequently may itself be compartmentalized into a majority (~90%) of truly depleted material, and a minority (~10%) of enriched material (the plum-pudding mantle).

The alternative might be to consider that the statistically most prominent group of basalts (neovolcanic N-MORB) represents most of the mantle, and that transform faults and seamounts tend to sample the minority extremes of truly depleted and enriched mantle. But why should this be? The nearly universal occurrence of melt lenses along the East Pacific Rise and their arrangement directly beneath fissured neovolcanic zones along the ridge axes seemingly compels mixing among magmas derived over broad regions, whereas seamounts and small volcanic structures in transform faults provide spot samples of the underlying mantle without magmas having to pass through 4 km of partly molten gabbro and a melt lens. The extent and scale of mantle diversity thus is blurred along ridge axes, and revealed at seamount clusters and small intra-transform volcanoes. Basalts erupted along ridge axes are still depleted, but not nearly as depleted as basalts that bypass the axial mixing regime. The mixing insures higher Nb/Y, Zr/Y and ΔNb among axial N-MORB even before significant differentiation occurs to produce parallel REE patterns at nearly constant Nb/Y and Zr/Y as MgNo decreases. Mixing is the reason that the array of hybrids at the East Pacific Rise in Figure 1D is oblique to the line of Fitton et al (1997). Simple calculations will show this.

First, does the oblique array result from mixing between truly depleted MORB and E-MORB only? The answer is no. With increasing proportion of E-MORB, a mixing calculation for the extreme compositions shown in Figure 1A predicts at first very little change in Zr/Y as Nb/Y increases - a nearly vertical relationship. At about 20% addition of E-MORB, the calculated trend flattens a bit. This is because on a log-log diagram of ratios, mixing trends curve and the proportional influence of small amounts of E-MORB on low concentrations of truly depleted MORB is very high. Thus initially it doesn't take too much E-MORB in mixes to increase ΔNb significantly. Perhaps 3-5% of E-MORB in the mix with truly depleted MORB will place the hybrid within or close to

the main data cluster. Nevertheless, no matter which truly depleted MORB is chosen, the resultant mixing trend *misses* the field for axial N-MORB at the Pacific-Antarctic East Pacific Rise. Since the mixing trend shown is calculated using the truly depleted MORB with highest Zr/Y, the misfit would be worse using any other truly depleted composition with lower Zr/Y. Furthermore, whereas mixing of 6-11% of E-MORB into truly depleted MORB will flatten REE patterns (models 1 and 2, respectively, bounding the brown field in Figure 1E), the light-REE portions of the calculated patterns are concave upward rather than downward.

To obtain concave downward patterns, mixing between some variety of silicic magma and truly depleted MORB is required. In Figure 1E, model 3 (bounding the top of the blue field) is a calculated mix of 90% truly depleted MORB and 10% andesite from Figure 1. The andesite itself, which has about 57% SiO_2 is approximately a 2:1 mixture between a very iron-rich basaltic liquid with about 50% SiO_2 and rhyodacite with about 70% SiO_2 (cf. Natland, 1991a). To emphasize this hybrid aspect of its composition in this discussion, I shall henceforth term it *ferroandesite*. That is, a possible mix with ferroandesite works out to about 92% truly depleted MORB, 5% ferrobasalt and 3% rhyodacite (model 4). This is almost equivalent to 93% truly depleted MORB, 5% E-MORB and 2% rhyodacite, which is to say that finding a unique mixing solution must probably futile. The resulting shifts in Nb/Y, Zr/Y and ΔNb are shown in Figure 1F.

If the concave downward REE patterns of most N-MORB are produced by small degrees of mixing with strongly differentiated liquids in axial melt lenses, the concave-downward shape of those patterns is clearly tied to the origin of those siliceous melts. The problem is complex and poorly understood. Crystallization differentiation, partial melting of hydrous mafic ocean crust, and late-stage liquid immiscibility have all been proposed to explain the origin of rhyodacite and affiliated ferrobasalt produced experimentally from MORB (Dixon and Rutherford, 1979; Spulber and Rutherford, 1983; Juster et al., 1989). The REE distributions are probably dependent on the influence of accessory phases that crystallize during the later stages of differentiation of basalt and gabbro (Delong and Chatelain, 1990), namely magmatic amphibole (pargasite), alkali feldspar, ilmenite, titanomagnetite, apatite, zircon, and perhaps others. Ilmenite in particular has a high partition coefficient for Y, and at some level its fractionation must

be important in causing reduction in TiO_2 contents and increases in SiO_2 contents among MORB silicic residua. This could be the cause for the small but distinct divergence of silicic compositions to the right in the data array for the East Pacific Rise shown in Figure 1D. Such divergence coupled with mixing pulls the overall MORB array without E-MORB into an orientation parallel to the line of Fitton et al (1997).

Mixing between primitive MORB and its own differentiated residua has rarely been considered, let alone understood to be an impediment to understanding of MORB mantle geochemistry. However differentiated depleted MORB may be, they are almost universally interpreted as probes of the mantle and related to peridotite by simple combinations of partial melting and crystallization differentiation. On a ΔNb diagram, the potential effects of mixing may seem subtle. However, consider one general result from the drilling of abyssal gabbro, namely that most of them are *ad*cumulates, with little or no retained interstitial melt (Natland et al., 1991; Natland and Dick, 1996; 2002). Because HFS elements are strongly excluded from crystals into melts, and almost all residual melt is then expelled from the lower ocean crust by a combination of crystal compaction and adcumulus growth, the effective HFS budget in the ocean crust is transferred almost entirely to the upper crust of basalts and dikes. Almost all Nb, for example, is there and not in the gabbros.   But how did it get there? It was first strongly concentrated in residual liquids at the melt lens, and there entrained by more primitive basalts *en route* to eruption, which removed it from the gabbros. Given that gabbros represent perhaps 75% of the ocean crust, this implies roughly a 4-fold enrichment of Nb in basalts and dikes compared with whatever its average concentration was in all magmas supplied to the crust from the mantle (both N- and E-MORB, and hybrids of them produced in the mantle). However, because of the modest retention of Zr in clinopyroxene, and the stronger retention of Y into both clinopyroxene and ilmenite, transfer of these two elements from the bulk of gabbroic cumulates into basalts and dikes is not as efficient as that of Nb. On the average, then, Nb/Y and Zr/Y of basalts and dikes along spreading ridges will be higher than in truly depleted MORB supplied from the mantle, thus average MORB will not precisely indicate mantle ratios.

Even so, whatever the mechanism of the origin of strongly differentiated melt in the ocean crust, and its potential for mixing with primitive basalt, the impact on Nb/Y,

Zr/Y and ΔNb is not really very great along the East Pacific Rise. Wholesale shift of depleted MORB from negative to strongly positive (Icelandic) values of ΔNb is not evident among the N-MORB spectrum of compositions.

The ΔNb diagram is not ideal for displaying the type of mixing described so far or for illustrating its prevalence. Any consideration of actual concentrations is more informative. Let at least one axis show a concentration. In Figure 2, log[Nb/Y] versus Zr, two data sets for the East Pacific Rise are considered, one combining three provinces for which high-precision ICP-MS data are available, the other all data, however measured, for samples from the well-studied segment of the East Pacific Rise between Siqueiros and Clipperton transform faults (~8.5°-10.5°N), and including off-axis seamounts. Both have the same features, two general trends, one between truly depleted MORB and E-MORB, the other branching less steeply toward the higher Zr concentrations of strongly differentiated compositions, mainly ferroandesite. Seamount data conform chiefly to the former; axial N-MORBs are more evenly divided, with prongs of data heading in both directions. The branch pointing toward higher Zr indicates the prevalence of mixing between primitive basalt and silicic compositions along the axial neovolcanic zone of the East Pacific Rise.

Note also that Nb/Y values of the ferroandesite compositions are about 0.1 (ΔNb ~ 0). This appears to represent the maximum effectiveness of all aspects of differentiation in the ocean crust including mixing to produce Nb enrichments in an environment dominated by truly depleted MORB. However, much higher Nb/Y and ΔNb occur at other places.

Could arrays between truly depleted MORB and E-MORB represent differences in extent of partial melting? Not according to the models of Fitton et al (1997); not, that is, if the mantle consists of a single homogeneous peridotite. Partial melting of a plum-pudding mantle, however, to produce trends parallel to their model trends but within the regional or local arrays of E-MORB and N-MORB separately, and subsequent blending of depleted and enriched magma strains might well obscure their separate Fittonian compositional vectors in Figure 1, C and D, and steepen the overall trend. Mixing with ferroandesite distorts the picture even further.

Fitton et al. (1997) based their MORB array in Figure 1C on depleted (N-MORB; MgO > 5%) compositions from three widely separate portions of the ocean floor, one in the Atlantic, one in the Pacific, and one in the Indian Ocean. Their modeling suggests that the difference between the Southwest Indian Ridge and Reykjanes Ridge, with the East Pacific Rise in between, is a matter of increasing the extent of partial melting, i.e., in response to cooler mantle supplying ridges in the Indian Ocean, warmer mantle beneath the East Pacific Rise, and even warmer mantle near Iceland. This is also the general conclusion reached by Klein and Langmuir (1987) and Langmuir et al. (1992) based on their melt-column modeling and consideration of regional differences in parental values of Na_2O and total iron as FeO (Na_8 and Fe_8, both corrected for fractionation to 8% MgO).

Crystallization histories of porphyritic basalt from Siqueiros Fracture Zone, however, suggest that the full range of parental compositions (the "global array" of Klein and Langmuir, 1987) is actually available within the reach of a single melting domain beneath the East Pacific Rise (Natland, 1989), and capable of supplying melt strains of quite variable composition to a single basalt. Like most xenolith suites, Alpine peridotites, and fracture-zone assemblages of abyssal peridotite, the mantle source of MORB cannot literally be homogeneous at all scales. It must be lithologically heterogeneous on the scale of a single melting domain, containing an array of fertile (lherzolitic) to refractory (nearly harzburgitic) lithologies, all of which can produce some type of basaltic liquid at the same temperature in a melting domain - a large range altogether - at a single location along the ridge axis. Compared with truly depleted MORB, magma mixing beneath the ridge axis produces a preponderance of slightly less depleted axial N-MORB that gives a false impression of mantle homogeneity amidst the likely heterogeneity.

In Figure 1D, the array of truly depleted MORB spans both the original array for the East Pacific Rise of Fitton et al (1997) in Figure 1C, and that of Reykjanes Ridge. In accord with Natland (1989), Figure 1D therefore indicates the presence of relatively fertile lherzolite and refractory harzburgite together in the same mantle beneath the East Pacific Rise. The Fitton et al. (1997) partial melting trend exists, but more than that, it *pre*-exists in peridotites on a local scale in the mantle. Thus some prior melting event, presumably an ancient one like formation of continental crust, explains the current local

variability. I take the scattering of truly depleted MORB to be representative of lithologic variability of depleted mantle beneath the East Pacific Rise. The depleted portion of the mantle beneath the East Pacific Rise is more like that of Reykjanes Ridge than previously realized, but it is leavened both with more fertile, yet still depleted, peridotite, and the sources of E-MORB. Discovery of very refractory shallow harzburgite in the mantle transition at Hess Deep (Dick and Natland, 1996; Arai and Matsukage, 1996) and yet which is associated with fairly typical N-MORB accords with this view. The variability indicated by the separate MORB data fields in Figure 1C, and the Na_8 evaluations of Klein and Langmuir (1987) and Langmuir et al. (1992) suggest that lithological variability of the mantle may also exist on a regional scale that has nothing to do either with current average extents of melting or mantle temperatures (Presnall et al., 2002).

Overall, ΔNb diagrams provide far more compelling evidence for mantle source heterogeneity than for homogeneity beneath the East Pacific Rise, and, together with these other techniques, provide convincing evidence that three varieties of magma mixing are important beneath spreading ridges: 1) mixing among magma strains derived from varieties of depleted peridotite; 2) mixing between these magmas and strains of E-MORB; and 3) mixing of primitive products of 1 and 2 with silicic melt in the vicinity of axial melt lenses. The latter two are evident in Figure 2. Models of partial melting based on the assumption of a homogeneous mantle do not encompass all the phenomena revealed by careful evaluation of ΔNb diagrams. The quantity ΔNb nevertheless is based on a circumstantial distinction between Icelandic tholeiite and certain depleted MORB that does not properly display their typical variation, in part because of properties of the diagram that tend to obscure or minimize the appearance of mixing relationships with enriched MORB and silicic lavas that until now have been left out of the diagrams.

ICELAND AND ADJACENT RIDGES

Magma mixing at Iceland

Besides being an emergent portion of the Mid-Atlantic Ridge and having crust up to 40 km thick, Iceland has a significant proportion, perhaps 10%, of silicic differentiates, much of it rhyolite, distributed among its basalts (Walker, 1963). The silicic rocks are mainly concentrated at Iceland's several dozen extinct and active central volcanoes, and are widely considered to be differentiates of the tholeiitic basalt that abounds at Iceland (e.g., Carmichael, 1964). I shall challenge this conclusion. The differentiation is thought to take place in large magma chambers beneath the central volcanoes, and the remains of some of these are exposed as plutonic complexes where older volcanoes are cut by glaciers. Lateral drainage of one such magma reservoir was responsible for the large Laki fissure eruption in 1783. Crystallization differentiation may also produce intermediate silicic rocks – andesite (also called icelandite) and dacite – but they probably more commonly result from mixing between basalt and rhyolite. Evidence for such mixing includes composite lava flows and dikes, quenched lava with differently colored blebs of basaltic and silicic material (so-called "emulsion rocks"), occurrences of pillows injected into coarse-grained silicic plutons, and complex interfingering of "acid" and "basic" constituents at interfaces between silicic and basaltic magmas that crystallized to coarse grain size in zoned plutons (e.g., Walker and Skelhorn, 1966; Yoder, 1973; Sigurdsson and Sparks, 1981; Marshall and Sparks, 1984; Macdonald et al., 1987). However, such intimacy nevertheless is no proof of a relationship between the two by crystallization differentiation in the crust.

Among Iceland's basalts, picrites are least removed from primitive parental compositions derived by partial melting in the mantle. They typically occur as small flows on fissure systems in between the central volcanoes (e.g., Breddam, 2002), where their feeders bypass most contact with the central vents. They are picrites in the sense that they have accumulated olivine phenocrysts, thus have MgO contents up to 23%, but plagioclase and clinopyroxene phenocrysts occur in many of the same rocks (e.g., Hansteen, 1996; Sigurdsson et al., 2000; Slater et al, 2001; Maclennan et al., 2003). The most magnesian Icelandic glass so far found, from Kistufell in central Iceland, has only 10.56% MgO (Breddam, 2002). Everything more magnesian than this likely has accumulated olivine. In further discussion, I shall term all analyses with >10% MgO as

"picritic", meaning "likely to have accumulated olivine phenocrysts" even though the IUGS definition of picrite based on chemistry has MgO ≥12%.

At Iceland as well as at several other flood-basalt provinces including Deccan and Karoo, basalt compositions vary because of both their extent of differentiation and parental attributes. One parental attribute that varies strongly is TiO_2 content. Petrologists thus distinguish low-Ti from high-Ti basalts at these places, but in fact there is a full continuum between them. Thus there are lower-Ti and higher-Ti basalts, and some rather arbitrary boundary between the two has to be chosen. At Iceland, both types include picrites (Figure 3A); those with highest TiO_2 are similar to ferropicrites of other flood-basalt provinces (e.g., Gibson et al., 2000). Whether all picrites crystallized from similarly primitive liquids might be questioned, but because TiO_2 also increases in residual compositions with extent of differentiation, an appropriate boundary should take into account both the effects of olivine accumulation in samples with high MgO content and of subsequent multiphase cotectic differentiation in samples with lower MgO content.

At Iceland, a significant proportion of picritic basalt has TiO_2 contents <1.4% (Figure 3A) and appears to form a group. If we take this group to have genetic significance, then 1.4% would be a reasonable maximum near-parental value for TiO_2 contents at, say, MgO = 8%.   Then for samples with <8% MgO we can assume a MORB-like multiphase cotectic relationship and calculate the parental parameters, termed Ti_8, Fe_8 and Na_8, correcting all differentiated basalts by means of average slopes to MgO = 8% using the linear relationships of Klein and Langmuir (1987) and Langmuir et al. (1992). Actual suite-specific calculations could be made using somewhat different slopes, but for the overall data very large data set, which includes data from dozens of localities for which the slopes are uncertain, this is neither practical nor feasible, and it would not result in significantly different estimated parental values.

Highest TiO_2 contents are in basalt with about 3.5% MgO content.   Thus for all basalt samples with >3.5% MgO, I define low-Ti basalt as having <1.4% Ti_8 and higher-Ti basalt as everything with greater Ti_8, and distinguish these by symbol in Figure 3A. Ti_8 can be calculated for picrites by assuming a predominant olivine-addition control (nominally ~Fo_{86} based on a linear regression of Al_2O_3, not present in olivine, to 0%

MgO for all picrites) and correcting TiO_2 contents by olivine subtraction. For this calculation, after considering other binary variation diagrams, I include samples having MgO contents between 8 and 10% with picritic compositions that are likely olivine controlled; the break between the two methods of calculation thus is at 8% MgO contents. I define rocks with analyses having <3.5% MgO and/or >55% SiO_2 as silicic (andesite, dacite, and rhyolite) and exclude them from the calculation. Figure 3A thus shows the differences between all basalts related to low-Ti and higher-Ti parents regardless of extent of differentiation or olivine accumulation. Among more than 2400 analyses of basalt in the GeoRoc Iceland data file, analyses of higher-Ti basalt exceed those of low-Ti basalt by a factor of about 1.5, but less than 5% of them are picritic, whereas nearly 25% of low-Ti basalt are picritic.

By these criteria, almost all basalt from Reykjanes and Kolbeinsey Ridges adjacent to Iceland to the south and north, respectively, is low-Ti basalt. Only a few rocks analyzed from Reykjanes Ridge have >1.4% Ti_8 and these are all north of the southern edge of the Icelandic shelf; there are none from Kolbeinsey Ridge. Many of the analyses are of glasses, none of which is picritic. Only four Reykjanes and Kolbeinsey whole-rock analyses are picritic. So far as is known, therefore, the entire region lacks picrite glass (>12% MgO). Nevertheless, Reykjanes and Kolbeinsey basalt can be distinguished from low-Ti Icelandic basalt. It is more MORB-like in general attributes, with somewhat higher SiO_2 and lower Na_2O at given MgO contents, lower Zr/Y, and somewhat higher REE concentrations.

On a ΔNb plot (Figure 3B), all data from both Iceland and adjacent ridges form broad curving arrays, with most primitive basalt including picrite lying on the steeper left-hand portions of the arrays. Basalt from Reykjanes and Kolbeinsey ridges has a sharper curvature than low-Ti Icelandic basalt, thus Reykjanes and Kolbeinsey samples fall toward higher Zr/Y for given Nb/Y, with many having negative ΔNb. Samples from Reykjanes Ridge north of 62°N, close to the Iceland shelf, systematically have positive ΔNb and were screened from inclusion with depleted basalts of Reykjanes Ridge south of 62°N by Fitton et al. (1997), only the latter being considered a variety of depleted MORB. However, whether sampled from south or north of 62°N, all basalt from Reykjanes Ridge is non-picritic, has low Ti_8, and stands apart from low-Ti Icelandic

basalt in terms of ΔNb. Therefore I group them together to illustrate that they actually form a curving array on a ΔNb diagram, and very like basalt from the EPR (when E-MORB are included), they cross the line for ΔNb = 0. Basalts north of Iceland along Kolbeinsey Ridge do the same, but without a gradient to positive ΔNb as the Iceland shore is approached; samples with both positive and negative ΔNb occur in close proximity.

Higher-Ti basalt falls along the flatter portion of the Iceland array at positive ΔNb, plotting at about the location of E-MORB for the East Pacific Rise. Silicic compositions are concentrated toward the upper right at high Nb/Y, with rhyolite *per se* having highest Zr/Y, but they have both positive and negative ΔNb. They partly overlap higher-Ti basalts, including some picrites. The silicic compositions appear to break into two trends at highest Zr/Y and Nb/Y; the trend with higher Nb/Y consists mainly of samples from Snæfellsness, an off-axis locality in western Iceland, and Örafæjökull, a volcano of the eastern rift.

Based on the previous evaluation of the East Pacific Rise, the great separation between most of the primitive basalt at one end of the diagram and rhyolite at the other cannot be the result of closed-system crystallization differentiation. Nor can these placements be the result of differences in extent of partial melting of a peridotitic source; rhyolite is not a melt of peridotitic mantle. By either simple process, rhyolite at Iceland is therefore unrelated to primitive (including picritic) low-Ti basalt.

Figure 3C shows estimated effects of mixing between two silicic compositions, one an andesite the other a rhyolite, and two primitive basalt compositions (small arrows). The compositions were selected because they lie at the extremes of the data array. Because this is a log-log ratio-ratio diagram, the mixing trends curve, but it is fair to say that their shapes and locations of particular intermediate mixing proportions depend strongly on actual end-member concentrations. The calculated curves thus provide examples only. Nevertheless, the effects of even a small amount of mixing, say 1-2% of either the andesite or the rhyolite, with primitive depleted basalt is clearly sufficient to effect a strong change in ΔNb. After that, a higher proportion of silicic material in the mixes accomplishes less of a change in ΔNb; the mixing curves flatten until they roughly parallel the line of Fitton et al. (1997) for ΔNb = 0, with one curve

above and the other just about on the line. The calculated mixing trends match the curving data array quite well (Figure 3B). Data for primitive basalt from two locations on Iceland, Theystareykir (northern rift) and Kistufell (central Iceland, over thickest crust) nearly parallel the line of Fitton et al. (1997) in Figure 3C, thus could conform to their partial-melting model. But their trend is also well reproduced by a calculated mixing trend (dashed green line) between more primitive basalt and 1-3% rhyolite.

A question raised in review is whether several of the Icelandic low-Ti basalts shown in Figure 3B, and including the one I have used for this calculation, actually have negative ΔNb. The concern is whether the Nb measurements are of sufficient quality at low concentrations, the data being, for example, neither recently obtained nor normalized, as is the practice of Fitton et al. (1997) and Fitton (this volume), to a well-known standard (G. Fitton, personal communication, 2006). The particular sample also fails a test of internal consistency with other trace-element determinations, notably the ratio Nb/La, an indication that Nb has not been properly measured. For this sample, I agree. Curving trends notwithstanding, there is indeed no evidence that any Icelandic basalt properly analyzed as a whole rock has negative ΔNb. Some olivine-hosted melt inclusions from Reykjanes Peninsula have negative ΔNb (Gurenko and Chaussidon, 1995), but again Nb measurements in inclusions at low concentrations are probably suspect. Other olivine-hosted inclusions from Theystareykir volcano in northern Iceland (Slater et al., 2001) may also have slightly negative ΔNb (Figure 3B), based on more precisely measured ion-microprobe determinations of La, and estimating Nb by assuming Nb/La from Theystareykir whole-rock compositions (Stracke et al., 2003; ppm Nb = 1.13*La - 012; correlation coefficient r = 0.97).

Whether some few data fall slightly below the line for ΔNb = 0 is beside the point. The more important question is why the Iceland trend is so flat. Apart from rhyolite, this comes down to asking why Icelandic picrites with very low concentrations of Nb, Y and Zr nevertheless have lower Zr/Y than basalt from Reykjanes and Kolbeinsey Ridges. More generally, what is it about Iceland that makes its most primitive basalt different in this way from that of its adjacent ridges?

My calculations also show that large shifts in Nb/Y and Zr/Y, and in some cases shifts in ΔNb from negative to positive values, can be accomplished by mixing small

amounts of rhyolite into primitive, depleted basalt at Iceland and along its adjacent ridges. However, this is only because - contrary to widespread and long-standing opinion - Icelandic rhyolite is not related to the basalt either by partial melting of a homogeneous peridotite mantle or subsequent closed-system crystallization differentiation. It has a very different origin, as discussed below. The situation thus is quite unlike that entailed by silicic compositions at the East Pacific Rise, which are too similar to basalts in Nb/Y and Zr/Y to affect ΔNb significantly by mixing, and which are plausibly derived from parental depleted MORB by crystallization differentiation.

We next need to consider whether the most important mixing is not necessarily between low-Ti basalt and rhyolite, but between low-Ti and higher-Ti basalt. This has to be appraised if only because rhyolite has almost no TiO_2, and simple mixing between it and low-Ti basalt cannot produce higher-Ti basalt. Rhyolite also has very low Sr concentrations, thus mixing with it could not change $^{87}Sr/^{86}Sr$.

A number of workers postulate that many non-picritic Icelandic basalts, most of them tholeiitic in the norm, are actually E-MORB, "alkalic", or "enriched", yet that rhyolites are derived from them by crystallization differentiation processes (e.g., Gunn, 2005). Favoring this is the juxtaposition on the ΔNb diagram of many higher-Ti basalts, including picrites, with silicic compositions. We have already seen how little effect crystallization differentiation has on shifting locations of basaltic and silicic lavas from the East Pacific Rise on a ΔNb diagram. If higher-Ti Icelandic basalt plots at the same positions as andesite, dacite, and rhyolite on such a diagram, then mixing of primitive low-Ti basalt with any of those magma types could potentially serve to shift their Nb/Y and Zr/Y. This possibility is similar to the inference we have already made about multi-component mixing along the East Pacific Rise, but at Iceland there are greater contrasts in the trace-element ratios between potential *basaltic* mixing end-members.

One distinction between rocks described as E-MORB at Iceland and the East Pacific Rise needs emphasis. Designation of any Icelandic rocks from higher-Ti basalt to rhyolite that plot atop each other on a ΔNb diagram as "alkalic" or comparable to E-MORB is somewhat misleading, since the basalts among them are all hypersthene-or even quartz-normative tholeiites, many being ferrobasalts. This is a hallmark of the entire North Atlantic Igneous Province and is consistent with the abundance of silicic

differentiates among the basalts. The entire concept of a "tholeiitic differentiation series" stems from the early, classic studies of these rocks.

Along the East Pacific Rise, E-MORB has more classically alkalic tendencies or attributes, including lower SiO_2 than vastly more abundant N-MORB, and nepheline in the norms of those with highest K_2O. The extreme compositions, at least, are undersaturated with respect to silica, and thus are not tholeiitic. From our prior discussion, so-called transitional basalt, or T-MORB, is likely a mixture between truly depleted basalt and Ne-normative alkalic basalt. The transitional hybrid may yet be hypersthene-normative, but the mixing end-members can still clearly be identified (Figure 1D). On near-ridge seamounts, the alkalic-basalt end member typically differentiates toward trachytic residua rather than rhyolite (e.g., Engel et al., 1965; Gee et al., 1991).

At Iceland, mixing with rhyolite also produces some geochemical attributes among higher-Ti basalts similar to those of Pacific E-MORB, and this has produced confusion. The difficulty is to discern whether basalt-rhyolite mixing has happened, whether alternatively such properties are intrinsic attributes of the basaltic mixing end-member, or, over the population of higher-Ti basalt, both. Functionally, in a place where mixing between basalt and silicic magma is so obviously an important process, it has to be excluded as an explanation for the geochemical attributes of any particular basalt in order to assign those properties to a source in the mantle.

To frame this difficulty in a more general way, the E-MORB conundrum at Iceland is but one expression of a general attribute of Icelandic lavas, namely that *their extent of differentiation based on virtually any standard of comparison, e.g., MgO content, MgNo, SiO₂ content, etc., correlates with their degree of trace-element and isotopic enrichment* (cf. Stracke et al., 2003). No matter what geochemical parameter is chosen, the average moderately differentiated basalt at Iceland is more enriched than primitive basalt, andesite is more enriched than moderately differentiated basalt, and rhyolite is more enriched than andesite. This should not be the case if shallow processes dominated by crystallization differentiation link all of these rock types, and it is also clearly unrelated to normative attributes of the rocks. O'Hara (1973) first noted this property of Icelandic basalt in connection with variability approaching Iceland along

Reykjanes Ridge (Schilling, 1973a; Hart et al., 1973), and he therefore proposed that shallow differentiation processes alone shifts ratios of trace elements and isotopes. Schilling (1973b), however, rebutted this view in favor of mantle source heterogeneity based on partitioning theory applied to mantle silicate minerals. Nevertheless, Schilling's argument applies to parental liquid compositions, thus fails to explain the correlation, which on his argument can then only be circumstantial.

Today, a many more data exist. Thus whereas trends along Reykjanes Ridge toward Iceland are gradational, and thus potentially explainable by along-axis mixing of two distinctive types of material at either end of the ridge, at Iceland proper the problem is compounded by the evident simultaneous availability of depleted low-Ti and enriched high-Ti basalt along short distances of the main Icelandic rifts, with high-Ti basalt being associated with rhyolite in central volcanoes. Thus rather than restricting evaluation of heterogeneity simply to basalt, so that we then consider only mantle sources to explain it, the data insist that the correlation of enrichment with differentiation extends to rhyolite, and that *local* mixing and assimilation involving strongly differentiated compositions in the crust must be important in producing geochemical diversity among Iceland's basaltic rocks. Recently, attempts have been made to select basalt samples to avoid such processes, but the effects of even tiny amounts of rhyolite mixed into primitive basalt are so striking that one may question whether assertions of a successful screening (e.g., Slater et al., 2001; Maclennan et al., 2003; Stracke et al., 2003) are too optimistic.

That rhyolite represents the extreme of so-called "enrichment" at Iceland is revealed simply by comparison of isotopes of Sr, Nd and Pb (Figure 4). The diagrams compare basalts with $^{87}Sr/^{86}Sr$ more and less radiogenic than 0.7034, picritic basalts (chiefly low-Ti with MgO >10%) and dacite-rhyolite (>62% SiO_2). The silicic compositions partly overlap the more radiogenic (higher-Ti) basalts, and everything with $^{87}Sr/^{86}Sr > 0.7034$, including rhyolite, falls in the range of Hart et al.'s (1992) FOZO (focal zone) mantle samples (the boundaries are from Bell and Tilton, 2002). But rhyolite claims the most enriched extreme on all diagrams. Both most-enriched basalt and rhyolite plot well away from Reykjanes-Kolbeinsey low-Ti basalts as well as Icelandic low-Ti basalt and picrite.

FOZO has been interpreted to indicate a common component in the mantle (Hart et al., 1992; Stracke et al., 2005; cf. Hanan and Graham, 1996). The surprise here is that *rhyolite* is the FOZO-like component at Iceland, with isotopic values matching the extremes of enrichments in basalt. As in Figure 3B, data for rhyolite split into two trends and the more basalts with more radiogenic isotopes replicate these trends. If one ignores the silicic lavas and refers only to basalts, then a mantle origin for the isotopic data arrays would be the only possibility to consider. But including the silicic lavas opens the possibility that the isotopic arrays are produced by shallow magma mixing among several magma types, rhyolite and other silicic differentiates being most enriched. Inference that high-Ti basalt owes its enrichment to something in mantle peridotite must be questioned, and the possibilities of mixing with silicic magma or crustal anatexis eliminated before an origin for the heterogeneity in peridotite can be accepted.

Now drawing this more sharply into focus, we might concede that the lineage from some (not all) higher-Ti basalt to some (not all) rhyolite could well be a shallow differentiation sequence (data points for many of them plot atop each other on the ΔNb diagram); further, that *any* representative of this lineage could mix with low-Ti basalt to shift ΔNb from negative to positive; and consequently that the ΔNb diagram provisionally reveals three fundamental basalt types in this region having different sources. These are: 1) depleted low-Ti tholeiite that erupts along rifts between central volcanoes; 2) depleted Reykjanes-Kolbeinsey low-Ti tholeiite that dominates spreading ridges beyond the Icelandic shelf; 3) and higher-Ti tholeiite that is abundantly associated with its own differentiated rhyolite and other silicic materials in central volcanoes. These correspond precisely to the three components based on isotopes inferred by Kempton et al. (2000) for Iceland, quoting but re-arranging, viz.: "1) a depleted component within the Iceland plume; 2) a depleted sheath surrounding the plume; and 3) one (or more likely a small range of) enriched component(s) within the Iceland plume (p. 255)". We could then say that 1-3 mixing occurs at Iceland, and that 2-3 mixing occurs along the Reykjanes Ridge. Only Group 3 has distinctly enriched chacteristics, but it is probably misleading to equate a ferrobasalt-rhyolite association with E-MORB of alkalic characteristics that erupts elsewhere along spreading ridges. If higher-Ti ferrobasalt and rhyolite ultimately have a common enriched source, then we must eventually come to understand how this

geochemically consistent range of materials originated with the following attributes: *1)*
strongly differentiated in bulk; 2) hypersthene- to quartz-normative; 3) high-Ti; 4)
rhyolitic residua; and 4) enriched geochemistry (e.g., high ΔNb, high $^{87}Sr/^{86}Sr$, high
light/heavy REE).

Influence of magma mixing on REE

Basalt-rhyolite mixing at Iceland produces precisely the same effects on rare-earth
elements as on ΔNb. The original argument of Schilling (1973a) that Reykjanes Ridge
records progressive enrichment in light REE approaching Iceland was based on a diagram
of chondrite-normalized Yb_N, which records the extent of crystallization differentiation,
versus $[La/Sm]_N$, which records source heterogeneity (rather than the subscript $_N$,
Schilling used the subscript $_{E.F.}$, standing for "enrichment factor"). A very similar trend
shows up when ΔNb or Nb/Y are plotted versus latitude. The full GeoRoc data file for
Iceland including silicic compositions is depicted in Figure 5A, as well as PetDB listings
for basalt from Reykjanes and Kolbeinsey Ridges. The diagram shows modest spread in
Yb_N for basalts (they are little to moderately differentiated) yet much variability in both
Icelandic and Reykjanes/Kolbeinsey $[La/Sm]_N$ (which should not change at all during
crystallization differentiation). Schilling's (1973a) argument is illustrated for the field in
blue, blown up in Figure 5B, with plotted points restricted to the Reykjanes/Kolbeinsey
data and one comparative data set for Theystareykir and Krafla volcanoes in central and
northern Iceland (Maclennan et al., 2003). The vertical spread of data accountable by
crystallization differentiation (variation in Yb_N) is given for one primitive and depleted
starting composition by the arrow labeled "gabbro fractionation".

The lateral spread in $[La/Sm]_N$, which Schilling (1973a) argued to indicate source
heterogeneity, is also reproduced by potential basalt-rhyolite mixing trends using two
different starting compositions and two rhyolites (OR135 and SNS17, respectively from
Örafæjökull volcano and the Snæfellsnes peninsula of western Iceland). These
compositions represent the two trends for rhyolites in Figures 3B and 4. About 3%
admixture of either rhyolite is sufficient to replicate both the Reykjanes/Kolbeinsey and

Theistareykir/Krafla data arrays. Among the basalts, mixing will also produce increases in $^{87}Sr/^{86}Sr$ that correlate generally with $[La/Sm]_N$ (Figure 5C).

Standard REE diagrams place some restrictions on potential magma mixing at Iceland. Crossing patterns occur in the Theistareykir/Krafla data set of Maclennan et al (2003) Figure 6A); among these I have chosen light-REE-depleted basalt TH8372, with 11.7% MgO contents, to represent a near-liquid primitive composition, and calculated REE patterns for different proportions of mixing with differentiated high-Ti ferrobasalt OR134, again from Öræfæjökull, with its steep REE pattern (Figure 6A), and rhyolite R-06, which also has an equally steep pattern (compare the flatter pattern of the andesite from the East Pacific Rise in Figure 1A), but with a pronounced Eu anomaly. Note the similarity in REE patterns of OR134 and E-MORB W03-21-2 from the East Pacific Rise. Note also the similarly fanning array of the entire data field for Reykjanes and Kolbeinsey Ridges, but that the heavy REE concentrations are higher than in TH9372. This difference could not be produced by mixing with any variety of differentiated lava, basaltic or rhyolitic, and thus reflects different sources for primitive and depleted compositions between Iceland and its adjacent ridges.

Small admixtures of either to TH9372 will very readily flatten the estimated REE patterns (Figure 6, B and C), but with the rhyolite admixture the patterns develop a steadily increasing Eu-anomaly. Not all Icelandic rhyolite has so pronounced a Eu-anomaly, but it is fair to say that individual Theistareykir/Krafla basalts either lack such an anomaly, or or if they don't, it is very small. Put another way, the maximum extent of possible rhyolite admixture into primitive basalt is probably about 5%, with relative REE concentrations (including a small Eu-anomaly) and Nb/Y (Figure 7) thereafter staying constant during shallow crystallization differentiation.

One thing rhyolite mixing cannot do, however, is increase the TiO_2 contents of any basaltic magma. The contrasting effects of possible mixing of TH8372 with both rhyolite R-O6 and high-Ti basalt OR-134 are shown in Figure 3A. Whereas high proportions of mixing beteween rhyolite and some basalt may well explain silicic compositions on the diagram with 4-6% MgO contents, no high-Ti basalt or picrite is likely to result from differentiation of a mixture between low-Ti basalt and rhyolite. And more than 20% admixture of titanian ferrobasalt OR134 with TH9372 is required to drive

the composition of TH8372 into the realm of higher-Ti basalt. On balance, mixing with high-Ti basalt is more likely than mixing with rhyolite to explain shifts in ΔNb and $[La/Sm]_N$ among primitive Icelandic basalts, but some basalt-rhyolite mixing undoubtedly occurs, and some, probably most, higher-Ti basalt should be viewed as having an independent and more enriched source than low-Ti basalt. However, the geochemistry of that source is likely diluted among the many Icelandic basaltic rocks that are hybrids between higher-Ti and low-Ti compositions.

The independence of the two basalt types is revealed well by considering the actual concentrations of magma types potentially involved in mixing, using – as we did earlier for the East Pacific Rise - diagrams of Zr versus Nb/Y. In Figure 8, A and B, I plot low-Ti and higher-Ti basalts (plus differentiates), and provide the mixing models for comparison in Figure 8C. There is no higher-Ti basalt with low Nb/Y, but there is some low-Ti basalt with high Nb/Y. The curvature of the low-Ti basalt data field in Figure 8A is well matched and almost identically by mixing between depleted compositions and either titanian ferrobasalt or rhyolite, but different proportions of the two are required.

In a diagram of $^{87}Sr/^{86}Sr$ versus Zr (Fisgure 8D), samples with Zr>200 ppm fall into two groups that have some geographic significance, viz., $^{87}Sr/^{86}Sr$ is about the same for all differentiated samples from the Vestmann Islands, but lower than among differentiated samples from Örafæjökull. Thus again, silicic compositions fall separately into two groups, separated by the upper dashed line. Comparable locations for the line in terms of Nb/Y are shown in Figure 8, A and B. Basalt with less-radiogenic $^{87}Sr/^{86}Sr$ than any higher-Ti basalt is delimited by another dashed line in Figure 8D, and labeled as Group 1. Again, this is an indication that higher-Ti basalt is distinctive from the outset, being somewhat more enriched isotopically and in other aspects of geochemistry than uncontaminated low-Ti basalt. In Figure 8A, note the distinctly lower Zr contents of Icelandic low-Ti basalt than in similarly low-Ti basalt of Reykjanes and Kolbeinsey Ridges. This adds to the picture of source heterogeneity among depleted compositions in the North Atlantic already evident from consideration of ΔNb and REE diagrams.

To summarize, heterogeneity among the sources of basalt in the Iceland region does exist, but ΔNb is not a geographical discriminant. One type of depleted basalt with negative ΔNb appears increasingly northward along Reykjanes Ridge approaching

Iceland to admix with higher-Ti basalt (or differentiates of it) having positive ΔNb. Kolbeinsey Ridge north of Iceland has the same type of low-Ti basalt, but with no indication of increasing ΔNb southward approaching Iceland. This abrupt discontinuity is probably the result of an offset of the Mid-Atlantic Ridge at Tjörnes Fracture Zone. Quite another type of depleted basalt with but also with near-zero or positive ΔNb is present at Iceland. This commonly mixes with the same type of higher-Ti basalt and probably also rhyolite. The Reykjanes/Kolbeinsey basalt type with negative ΔNb is not present between the northern and southern shelves of Iceland.

Other Trace Elements

Chauvel and Hémond (2000) used pairs of trace-element ratios to illustrate their thesis that recycled abyssal gabbro as eclogite is present in the Iceland melt source. The pairs they chose combine Y, rare-earth elements and HFS elements in various combinations, including a ΔNb diagram, and all embody small contrasts in bulk-distribution coefficients during shallow crystallization differentiation and partial melting of peridotite. Their general point is that mantle ratios for most of their pairs are very restricted; that this consistency should be imparted to mantle melts; and thus that spreads in the ratios entail some phase control on partitioning beyond that possible with only a peridotite source. Mixing between melts derived from peridotite and recycled abyssal-gabbro cumulates is one way to explain the diversity in trace-element ratios. Their argument was restricted to variations among basalts.

Figure 9, A-F, compare several of these ratios plotted against Zr/Y for comparison to ΔNb, but with silicic compositions included. As in the ΔNb diagram, the data arrays slope, and trends for the primitive basalt suites of Theistareykir and Kistufell fall along the arrays. The principal groupings of low-Ti basalt, higher-Ti basalt, Reykjanes-Kolbeinsey basalt, and silicic compositions occupy the same relative positions that they do on a ΔNb diagram, thus the same arguments made earlier about potential mixing relationships can be made for each of them; the spreads could be caused by mixing between depleted low-Ti basalt and either evolved higher-Ti basalt or rhyolite. The ratios Rb/Cs and La/Ta do not vary between primitive Icelandic basalt and rhyolite, but that

means they are still consistent with the possibility of such mixing. Particular suites such as that of Theistareykir (Stracke et al., 2003) have Ba/Th diminishing with increasing Zr/Y, thus pointing toward rhyolite, but the GeoRoc data set as a whole does not show a consistent relationship between the two ratios, perhaps indicating interlaboratory analytical differences.

Slater et al. (2001) observed far greater variability among light-REE (and elements with similar partition coefficients) than among heavy-REE (and elements with similar partition coefficients) in phenocryst-hosted melt inclusions in basalt from Theistareykir, and observed that such variability cannot be caused by shallow crystallization differentiation; again, absolute concentrations of these elements can be changed appreciably by fractionation, but not their ratios. The observed variability of the melt inclusions, however, is exactly that shown by the spreads in any of the trace-element ratios in Figure 9. Slater et al. (2001) concluded that the "obvious explanation of this behavior is that it results from fractional melting…(p. 345)". I say instead that the explanation is magma mixing involving primitive depleted basalt and strongly differentiated basalt or rhyolite. This also will shift ratios of strongly incompatible elements to the more compatible elements, and is the more obvious choice for Iceland where such mixing is abundantly described in the literature. Slater et al. (2001) used principal component analysis to establish that most variance in trace elements of Theistareykir basalt depends on a component dominated by light REE, with the second component being dominated by the heavy REE. This is because the light REE are more affected by a silicic admixture or contaminant than the heavy REE (Figure 6). Beyond that, the case for mixing implied by principal component analysis is quite eloquent, predicting among other things greater variance of melt inclusions than host basalts; it is just that the mixing is not among instantaneous fractional melts of a peridotite mantle source.

Stracke et al. (2003) noticed strong correlations among incompatible trace-element concentrations and ratios, isotopic ratios, and aspects of major-element composition in basalt from Theystareykir. They explained these correlations using a melt column model in which enriched basalt is derived from low partial melt fractions at higher pressure and depleted basalt is derived from greater partial melt fractions at lesser

pressure. This is a melt-column model similar to that of Klein and Langmuir (1987) for MORB. At this juncture, needless to say, I prefer instead that the observed correlations of trace-element ratios that are indicative in general of "enrichment", to increases in major oxides such as TiO_2 and K_2O contents, and to the decreasing CaO/Al_2O_3 and SiO_2/FeO, as noted by Stracke et al. (2003) can all equally well be explained by mixing between primitive basalt and either strongly differentiated Icelandic ferrobasalt or silicic magma.

Overall, this means that melt fraction, pressure, and potential temperature cannot be adduced for these rocks by inversion especially of rare-earth patterns to specific mantle compositions. I judge that most such patterns are too strongly influenced by shallow mixing processes to infer the intrinsic properties of whatever aliquot of them represents a mantle source. Besides this, at Iceland if anywhere the isotopically multi-component source is not likely to be lithologically homogeneous (Anderson and Natland, 2005) as inversion models require (McKenzie and Bickle, 1988), and it may not even be peridotite.

A potential shortcoming of principal component analysis using mainly REE is that by itself it does not seem able to discriminate between the effects of mixing involving a generalized silicic end component and mixing with an E-MORB or more generalized alkalic end component of the type I have discussed for the East Pacific Rise. In both cases, the light REE have greater variance than the heavy REE.   Thus Sclater et al. (2001) obtained fairly similar first and second principal components for places as disparate as Iceland, the FAMOUS and MARK areas in the central North Atlantic, and the Gorda and Juan de Fuca Ridges in the Pacific.

The mixing story has to be compatible with data on isotopes. Briefly, there are strong correlations (or anti-correlations) between $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{176}Hf/^{177}Hf$, and $^{206}Pb/^{204}Pb$ with Zr/Y, with rhyolite occupying the more radiogenic end of each data field at high Zr/Y. Considering just $^{87}Sr/^{86}Sr$, tholeiitic ferrobasalt, andesite (icelandite), and dacite have much higher concentrations of Sr (400-600 ppm) than rhyolite (<100 ppm), thus seem likelier to increase $^{87}Sr/^{86}Sr$ by mixing with undifferentiated low-Ti tholeiite (~50-70 ppm Sr). A rough calculation indicates that $^{87}Sr/^{86}Sr$ can be increased from

0.7028 to 0.7031 – which is fairly representative of Icelandic tholeiite - by mixing between basalt with ~50 ppm Sr and about 10% of anything at Iceland with ~500 ppm Sr.

Central to this story, two mixing components that differ by 450 ppm Sr cannot be related by shallow crystallization differentiation involving plagioclase. That is, in general among Icelandic tholeiites, Sr behaves like K, Rb, Ba or any other incompatible element; it actually tracks Ti_8 fairly closely. However, once whatever primitive magma is emplaced at crustal levels, crystallization differentiation involving plagioclase takes effect, and thus *locally* Sr concentrations remain nearly constant through most subsequent stages of differentiation, being buffered to nearly constant levels principally by the contrasting partitioning controls of cotectic plagioclase and clinopyroxene. The local constancy represents a *preset* but regionally quite variable parental Sr concentration. Among parental liquids, however, Sr is not buffered by plagioclase, which indicates a distinctive evolution below the depth of plagioclase stability, that is, beneath the seismically measured crust in the upper mantle. Most high-Ti basalt, or primitive (ferropicritic) precursors (but very likely differentiated high-Ti ferrobasalt itself), passes untrammeled through the mantle-crust transition at Iceland.

Finally, Stracke et al. (2003) indicate that the enriched component involved in magma mixing at Theistareykir has HiMu isotopic attributes (high $^{206}Pb/^{204}Pb$, indicative of high U and Th concentrations in melt sources). Later, Stracke et al. (2005) modified this view, construing HiMu localities in the ocean basins to be few (St. Helena, Tubuai) and not including Iceland. Elsewhere including Iceland, FOZO should be considered the more usual mixing end component with somewhat high $^{206}Pb/^{204}Pb$.   Silicic magma at Iceland has this attribute (Figures 3 and 9G).

Gabbro-sourced basalt at Iceland?

Chauvel and Hémond (2000) and Breddam (2002) found similarities between the trace-element and isotope geochemistry of primitive Icelandic tholeiite, mainly picrite, and depleted abyssal gabbro. They proffered the model that enriched Icelandic tholeiite is derived by partial melting of upper ocean crust (basalts and dikes) in the melt source, whereas low-Ti basalt derives from partial melting of lower ocean crust (gabbro

cumulates) and mantle harzburgite together. Thus a "complete section of ocean crust" seems to be present in the melt source, probably as eclogite, an interpretation adopted by Foulger et al. (2005a, b) in order to speculate on how such material might have been emplaced beneath Iceland in consequence of plate-tectonic processes. Both Chauvel and Hémond (2000) and Breddam (2002), however, favored recycling of ocean crust from the lower mantle after its emplacement there by deep subduction, and subsequent entrainment in an ascending mantle plume.

I wished to discover whether primitive Iceland basalt with lower Zr/Y than Reykjanes-Kolbeinsey basalt (Figure 3B) matches the general description of gabbro-sourced basalt provided by Chauvel and Hémond (2000) and Breddam (2002). The comparison depends on a general similarity between trace-element patterns of primitive Icelandic tholeiite and abyssal gabbro cumulates. A key indicator is that the basalts should have high Sr/REE, or Sr/Nd, in consequence of the high partition coefficient for Sr for plagioclase that originally crystallized in the ocean crust now presumed to have been recycled down and up through the mantle beneath Iceland.

GeoRoc contains 58 analyses of samples from Iceland with Zr/Y < 1.8, that is, less than in Reykjanes/Kolbeinsey basalt, and almost all of them are picritic (>10% MgO). These have 0.40%<Ti_8<0.75% with an average Ti_8 = 0.63%. These are values so low that they are only matched by a tiny fraction of MORB. They are distributed mainly in the Reykjanes and northern volcanic zones, with only two being analyzed from the eastern volcanic zone. Of these samples, 39 have also been analyzed for Sr and REE. Marked positive Sr-anomalies show up well in trace-element patterns of all these picritic lavas when normalized to primitive mantle (Figure 10A), as they do in modern abyssal olivine-gabbro and troctolite adcumulates (Figure 10B). Indeed, they are more pronounced than in any of the several samples in which Sr-anomalies were discovered by Chauvel and Hémond (2000) and Breddam (2002), all of which have higher Zr/Y. No such anomalies are present in typical MORB or in higher-Ti Icelandic tholeiite. Figure 10A also shows that the Sr-anomalies in Icelandic picrites are as strongly pronounced as ones in mineral-hosted melt inclusions from northern Iceland (Sigurdsson et al., 2000; Slater et al., 2001) and olivine-hosted melt inclusions from Mauna Loa, Hawaii (Sobolev et al., 2000). Sigurdsson et al. (2000) inferred that some of the Icelandic inclusions, those

which have $CaO/Al_2O_3 > 1$, require a pyroxenite rather than a peridotite melt source, and Sobolev et al (2000) inferred an origin for the Hawaiian inclusions in eclogite, with the Sr-anomaly indicating the effect of "ghost" plagioclase occult in a formerly gabbroic assemblage now too deep beneath the Pacific lithospheric plate for plagioclase to be stable. Even though the Sr anomalies of Icelandic picrites are positive, Sr concentrations themselves are still low (average 66 ± 20 ppm), about half that in the MORB suite from the Pacific-Antarctic East Pacific Rise considered in Figure 1. Another point of comparison is the low Zr/Y itself (Foulger et al., 2005a, b), which in abyssal olivine gabbro is a consequence of concentration of these two elements in cumulus clinopyroxene and absence of a significant residual melt fraction in rocks that are adcumulates.

In general, potential gabbro-sourced basalt, mainly picritic, is *the* predominant truly primitive and ostensibly highest-temperature lowest-Ti tholeiite at Iceland. It occurs along all the principal rifts, although it is less common on the eastern rift, and it is distinct from low-Ti basalt of Reykjanes and Kolbeinsey Ridges. It has geochemical attributes similar to low-Ti mineral-hosted melt inclusions also occurring in Icelandic low-Ti picrites.

Precise comparisons between the trace element patterns of picrites and abyssal gabbros is difficult because the former are mainly basaltic liquids with some percentage of accumulated olivine, whereas the most nearly similar gabbros are mainly assemblages of accumulated minerals with almost no retained liquid. If the latter are construed as a melt source for the former, then some partitioning model needs to be developed to infer the trace element concentrations in partial melts of those gabbros; the gabbro and the partial melt will not be equivalent. We should be comparing model melts derived from gabbro with picrites. Thus in Figure 10A, the aggregate of trace element patterns, apart from Sr, slopes consistently downward to the left, toward lower Ba, Th, and Nb, whereas among the gabbros the distribution through the heavy and intermediate rare-earths is flatter, and it abruptly drops downward toward Ba, Th and Nb. Among the picrites, Nb and La have about the same normalized concentrations, whereas among the gabbros normalized Nb is less than La. Does this mean that the picrite melt source is relatively enriched in Nb (thus providing even highly primitive melts positive ΔNb)? Should we

even expect that these details of the gabbro patterns could be retained in partial melts of recycled gabbro? Should they be retained if melting occurs in the eclogite facies? The gabbros depicted in Figure 10B are from a particular location and crystallized from only a small spectrum of the global diversity of MORB. Other abyssal gabbros may be different.

Let us suppose, however, that the patterns for picrites fairly mimic those of their source. Then the Sr-anomaly is best explained by derivation of the picrites from a gabbroic or eclogite source. But then also the downward trend toward the left among picrite rare-earth elements is an indication that the principal phase in the source containing rare-earths, namely clinopyroxene, had an even steeper downward slope in the same direction (e.g., Johnson et al., 1990). This is not an attribute of the gabbros shown in Figure 10B. The source gabbros of the picrites crystallized from more refractory liquids than typical MORB, with stronger depletions in light rare-earth elements.

At the same time, Ba, Th, and Nb – all three, are more enriched with respect to rare-earth elements in the Icelandic picrites than in the abyssal gabbros. Thus positive ΔNb of the picrites is an attribute indicating some, albeit very slight, relative enrichment in all of these elements with respect to depletion in rare-earth elements, when compared with abyssal gabbro. Chauvel and Hémond (2000) argued that positive ΔNb in primitive Icelandic tholeiite actually indicates depletion in Zr, but the full trace-element patterns suggest that two processes acted simultaneously: depletion in Zr along with light and intermediate rare-earth elements, and a bit of an enrichment in Ba, Th, and Nb. Neither is an attribute of abyssal gabbro, at least those shown in Figure 10B.

How was the slight enrichment in Ba, Th, and Nb accomplished? Here, the very low concentrations of the particular elements, and the difficulties of analyzing them precisely at such low concentrations, come into play. A very slight amount of mixing with, or assimilation of, rhyolite or other silicic material cannot be excluded. Neither can slight incorporation of an alkalic E-MORB component. For that matter, neither can slight incorporation of incremental fractional melts derived from peridotite, even if the principal trace-element attributes are established by partial melting of a thoroughly depleted eclogite. On balance, I favor the option that some slight amount of rhyolite incorporation has occurred, because it is a demonstrated process at Iceland, it is consistent with mixing

trends expected on the basis of trace elements and isotopes elaborated earlier, and because of the lithological heterogeneity that I believe can be expected of eclogite remnants recycled from either oceanic or continental crust, and from which partial melts must aggregate. I shall return to this point shortly.

Origin of three basalt types at Iceland and adjacent ridges

Figure 11 shows values of Ti_8, that is, TiO_2 contents corrected for fractionation to nominal parental compositions with 8% MgO, plotted against similarly corrected values of Fe_8 and Na_8. This includes picrites, as explained before. The arbitrary distinction between low-Ti and higher-Ti basalts with a boundary at 1.4% Ti_8 usefully discriminates parental picritic compositions (Figure 3A), and links all subsequent differentiates to the range of parental basalt types at Iceland. Based on prior discussion, the complete gradation between extreme low-Ti and high-Ti basalt types may be a consequence of mixing, but this diagram shows that there is an underlying and considerable parental variability. However, a true enriched high-Ti parental basalt type with, say, >4% Ti_8 and with picritic variants does indeed exist at Iceland, as does depleted low-Ti parental basalt with <0.5% Ti_8. Bearing in mind that the diagrams are based on whole-rock compositions, some of the scatter in Fe_8 and Na_8 may result from alteration (e.g., to sodic spilite or basalt partly transformed to iron-rich clay minerals, this proportionately reducing MgO contents and enhancing the fractionation correction), basalt-rhyolite mixing (lower Fe_8) or addition of plagioclase phenocrysts (again, lower Fe_8). The principal observation to make, however, is that Ti_8 varies by about a factor of 10 at essentially constant Fe_8 and Na_8, with the latter centered on low values of 1.5-2.5%.

The constancy of Na_8 and Fe_8 over the wide range in Ti_8 is especially difficult to explain by melting models that use peridotite as a starting composition. Langmuir et al. (1992) produced a strong correlation in their models between Na_8 (from 3.8 to 1.6% as the aggregate melt fraction increased) and Ti_8 (from 1.8 to 1.0%) using a starting composition with 0.15% TiO_2, about the same as in the starting composition (McDonough and Sun, 1995) assumed by Fitton et al. (1997). However, compare the data fields in Figure 11 with the fields of the global array for MORB, shown here for

Indian Ocean MORB, and the general trends, shown as red arrows for melt-column models of Klein and Langmuir (1987) and Langmuir et al. (1992). The Indian Ocean MORB field in Figure 11B is broken into three portions corresponding to three parental basalt types with respectively higher Na_8 (Mahoney et al., 1989; Natland, 1991b). The MORB global array is provided by an increasing extent of partial melting of a homogeneous peridotite source under the influence of temperature, with the highest temperature represented by samples with least Ti_8 and Na_8 of Type 1 Indian MORB. Nevertheless, all MORB have <2% Ti_8 and most have <1.4% Ti_8, consistent with the models of Langmuir et al. (1992). Klein and Langmuir (1987) attributed basalt from Reykjanes and Kolbeinsey Ridges to the low-Ti_8 end of the global array (corresponding to Type 1 Indian Ocean MORB), and in their model this is related to other more sodic and titanian parental MORB by a higher average extent of partial melting of peridotite near warmer mantle plumes. Later, I shall propose an alternative.

The melt-column model, however, does not reproduce the very high Ti_8 at nearly constant Na_8 of much Icelandic tholeiite. Indeed, by itself it contravenes the modeling of peridotite partial melting of Fitton et al. (1997) that was designed to show mantle heterogeneity using ΔNb. Partitioning relationships during melting between basaltic melt and major mantle silicate phases including garnet during fractional melting (Figure 1C) cannot produce such extreme variability in Ti_8 either in the liquid or in residual peridotite. Melting of commonly construed peridotite in the upper mantle is obviously inadequate to account for the Ti_8 variability of Icelandic basalt. Stracke et al. (2003) also developed a melt-column model for Theistareykir, but did not consider basalt in which $Ti_8 > 2\%$. Even so, neither their model nor the data from Theistareykir resemble either the global or local trends for MORB shown in Figure 11.

I propose that the Ti_8 variability reflects the influence of a readily melted Ti phase in the source. Add this phase to olivine, pyroxenes and an aluminous silicate (plagioclase, spinel, garnet). For the highest values of Ti_8, say above 3%, only the oxide minerals ilmenite (ca 45% TiO_2) and titanomagnetite (20-30% TiO_2) at low pressure and rutile (pure TiO_2) at high pressure are likely to have a strong influence on this aspect of melt compositions. Magmatic pargasitic amphibole with up to 3.5% TiO_2 in a somewhat hydrous source might also contribute. However, none of these minerals are usually

construed to occur even in mildly enriched (or metasomatized) peridotite sources of tholeiitic basalt. They were not, for example, in the models of Fitton et al. (1997).

If not in peridotite, where could the Ti phase or phases reside? In the ocean crust, gabbro cumulates contain as much as 20% of oxide gabbro. These have as much as 30% of ilmenite and titanomagnetite combined, plus perhaps 1-2% pargasite (e.g., Natland et al., 1991; Natland and Dick, 1996; 2001). These are at the low-temperature end of gabbroic differentiation in slowly spreading ocean crust, and typically occur as deformed seams cross-cutting nearly oxide-free olivine gabbro. They also occur in close proximity to tonalite/trondhemite veins. This is because the two represent similar and perhaps even identical stages of differentiation, especially if they are complements produced by liquid immiscibility (Natland et al., 1991; Natland and Dick, 2001, 2002). In any case, they are loci of highest concentrations of incompatible elements (Natland and Dick, 2002), especially HFS elements locked by coupled substitution into clinopyroxene and LIL elements in sodic to potassic feldspars. The silicic veins, which contain zircons, have the highest HFS concentrations of all (Niu et al., 2002a). If this association, or any similar association produced in a continental setting, were to wind up in the mantle by means of subduction or any other process, the HFS enriched zones of oxide gabbro and silicic veins would simultaneously provide the earliest melts during fractional melting, and the most enriched basaltic compositions, even if the assemblage were transformed to the eclogite facies.

Both Chauvel and Hémond (2000) and Breddam (2002) have proposed aspects of this hypothesis. They postulate that melting of "complete sections of ocean crust" is required to explain basalt geochemical variability at Iceland. They proposed that low-Ti basalts carry the trace-element and isotopic signature of abyssal gabbros whereas higher-Ti basalts carry those of altered abyssal tholeiites occurring as flows and dikes in the ocean crust. They assumed that all of this material is present in the melt source via recycling first through subduction down through the entire mantle and then up again in an ascending deep mantle plume (cf. Leitch and Davies, 2001).

Foulger et al. (2005a, b) supported one aspect of this geochemical model by noting the strong similarity of many low-Ti basalts in concentrations and ratios of Y, Nb, Zr, and Ti to abyssal olivine gabbro and troctolite, and the difficulty of extracting these

concentrations and proportions from peridotite. I have already discussed the problem of positive ΔNb in Icelandic picrites. A greater difficulty, however, lies in explaining higher than expected concentrations of Nb in higher-Ti basalts. For this, Foulger et al. (2005b) proposed that E-MORB like that of the East Pacific Rise is sufficiently present in bulk or average ocean crust to provide a preferential enhanced increment of Nb (and similar elements) to initial fractional melts of ocean crust subducted and abandoned in a proto-Icelandic zone of collision of continental lithosphere.

Now, after considering that melts with both high Ti_8 and high ΔNb are required to explain higher Ti basalt, and the possibility that low-Ti Icelandic picrite derives from olivine gabbro cumulates transformed to eclogite, I suggest another possibility.   First, a more enriched material than ocean crust is indeed present among the sources of Icelandic basalt. But I suggest that its lithology is more like that of oxide-rich titanian ferrogabbro veined with silicic materials than E-MORB of alkalic affinity. Partial to complete melting of this material produces the essence of high-Ti basalt, and this blends in varying proportions with low-Ti basaltic magma derived from one or more depleted sources beneath Iceland. I suggest that oxide-rich gabbro was originally a part of deep continental crust, and formed during ancient differentiation of sialic components of that crust. I propose that some of this material is now present as delaminated lower mafic continental crust in the central North Atlantic beneath Iceland. Also, some silicic material is still intimately associated with this delaminated continental crust in the Icelandic melt source, perhaps as veins, pods, or Skaergaard-like "sandwich horizons" (Wager and Deer, 1939) in gabbro or granulite of gabbroic composition, or at least as partially assimilated country rock; these contribute to the abundance of Iceland's rhyolites, set its isotopic signature and give it higher Nb/Y *by an order of magnitude* than that of silicic material in the ocean crust. Origin of the enriched characteristics including high ΔNb thus is tied to origin both of titanian basaltic magma and of silicic differentiates in ancient continental crust, and is a consequence of modern blending of diverse strains of magma extracted either fractionally or by batch melting from this heterogeneous protolith. With this, Icelandic picrites are derived by more extended fractional melting from residual olivine gabbro, or its eclogitic equivalent, after extraction of the components of oxide gabbro and associated felsic veins.

The heterogeneous protolith is the key to the mixing relations described herein. It effectively provides a *pre-differentiated and pre-mixed* body of rock, with all stages of differentiation present even in short sections of the gabbroic or eclogitic assemblages, and from which the character of mixing end-members is provided. An olivine gabbro that is intimately veined around grain boundaries with tonalite or trondhjemite cannot fail, even as eclogite, to produce a partial melt without at least a slight signal of a silicic component in its geochemistry. Fractional melting models have always been based on an assumption of lithologic heterogeneity of the melt source. As I have argued elsewhere (Natland, 1989), however, this is unlikely even for the depleted peridotite sources of MORB, and for gabbro cumulates it is contravened by almost every description of such rocks in the field that has ever been written. Therefore *begin* with the assumption that the source is lithologically heterogeneous at the outset, and the models will at least to that extent correspond better to Nature. Adding such complexity to the source simplifies our picture of the melting process by placing all source lithogies in a single body of rock within the melting domain. It also means that the sequence from rhyolite through higher-Ti ferrobasalt to primitive olivine tholeiite at Iceland is fundamentally a partial melting sequence and, in consequence, that both rhyolite and higher-Ti ferrobasalt do indeed cross from the mantle into the crust at depths of 10-40 km beneath Iceland. This is implicit in the model of Fitton et al. (1997), except that it cannot occur if the source is merely peridotite.

Reykjanes and Kolbeinsey low-Ti basalts still appear to have a peridotite source, but it may actually be that of detached or delaminated subcontinental lithosphere rather than the high-temperature end of the MORB global melting array. The low-Ti basalt of Iceland approaches abyssal gabbro in its HFS trace-element attributes, and this could still indicate the presence of some sort of trapped or detached ocean crust in melt sources beneath Iceland. Altogether, however, this source appears to be more refractory than typical abyssal gabbro, and slightly more enriched, thus I favor, albeit provisionally, a provenance for it also within the lower continental crust, and thus in immediate proximity to oxide-gabbro and silicic components inferred from high-Ti basalts and enriched icelandite, dacite and rhyolite. ΔNb relationships show no significant present-day influence of depleted MORB mantle, or even of peridotite sources of Reykjanes and

Kolbeinsey basalt, in melt sources directly beneath Iceland, in accord with conclusions based on isotopes of Kempton et al. (2000). I thus offer the tentative conclusion that Iceland presents an array of basaltic rocks derived from sources originally in lower continental crust, but probably not peridotite, within a "sheath" of basaltic rocks derived from delaminated subcontinental peridotite.

ON DELAMINATION

In addition to subduction, I suggest that fundamental heterogeneity of the upper mantle is caused by separation and disaggregation of continental crust and subcontinental lithosphere, and that this was the case in the North Atlantic. I offer this as an alternative to a mantle plume for Iceland and the North Atlantic Igneous Province. I take this opportunity to explain more fully how I envision this process, and how it relates to the petrogenesis of Icelandic tholeiites and silicic volcanic rocks discussed here.

As scientists, we prefer simple models, or perhaps have biases favoring simple ideas. One of these is that rupture of continents produces knife-edge discontinuities – granitic continents on two sides, depleted MORB ocean crust in the middle. This is hardly likely to be the case, given the existence of microcontinents like the Seychelles (see Holmes, 1928), submerged banks of continental crust coated with flood basalt and peraluminous rhyolite like Rockall Bank (Roberts, 1975; Hitchen et al., 1998), or with alkalic basalt and trachyte like Jan Mayen just north of Iceland in the North Atlantic (Talwani and Eldholm, 1977; Maaløe, 1986; Kodaira et al., 1998) and direct petrochemical evidence for incorporation of components of continental crust in basalts of Kerguelen in the Indian Ocean (e.g., Frey et al., 2002). Beneath each granitic outlier, some thickness of lower continental crust must reside, and beneath that, a portion of subcontinental lithospheric mantle. No great stretch of the imagination is required to postulate that smaller bits and pieces of continental material become entrained in convecting upper mantle that moves in around all of these abandoned fragments and microcontinents to supplant drifting continents.

"Delamination" is an odd word, implying, as I would think, stripping off of a layer along a curved surface concentric with the surface of Earth, like peeling the plastic

from a driver's license. Yet it is the word that has been in use now for nearly two decades to explain the wide distribution of certain types of chemical heterogeneity in the crust of the Indian Ocean in the lee of drifting Greater India (e.g., Mahoney et al., 1989). The term has also been applied to orogens to mean sinking of pieces of the lower crust into the mantle (Kay and Kay, 1991, 1993; Rudnick, 1995). Synonyms for this process, which nevertheless have nothing to do with layers, are foundering (Daly, 1926), major stoping (Daly, 1933), peeling off (Schott and Schmeling, 1998), dripping into mantle downwellings (Zandt et al., 2004), arc-root foundering (Zandt et al., 2004) and convective instability (Jull and Kelemen, 2002; Saleeby et al., 2003). Anderson (2005 and this volume) invokes eclogite foundering from the base of drifting continents as a major mechanism imparting heterogeneity to the upper mantle.

Most workers have emphasized that the density of mafic lower crustal igneous assemblages and some granulites can be higher than that of mantle rock, although Daly construed this in terms of the contrast between solid mafic rock and his presumed vitreous basaltic substratum. Nowadays, the contrast is between rocks in the solid state, viz., eclogite and garnet pyroxenite in the lower crust are denser than peridotite. Jull and Kelemen (2002) emphasize that sinking of dense lower crustal materials will only happen at elevated temperature (at least 500°C but more usually 700° or higher), but that this could occur under conditions at arcs, rifted continental margins, and regions of continents undergoing extension. Mainly this means that all granulite associations, which certainly occur pervasively in continental crust at depth, could have been subject to such stresses at some point in their histories, and that therefore a significant fraction of continental crust may have recycled back into the mantle by this process and subduction combined (Hamilton, 2003).

Daly (1926, 1933), whose views on tectonic processes were closely tied to an important question of his day, namely isostasy, was certainly the first to indicate that uplift would accompany the detachment and sinking of blocks of dense lower crust into the substratum. This is nothing other than the casting off of ballast, a process known to anyone familiar with boats and ships, and, as it seems to me, a plausible alternative to the hypothesis of thermal uplift thought to accompany plume impact (e.g., Campbell, 2005). Recent workers, for example, use it to explain uplift of the Colorado Plateau (Bird, 1979)

and the Sierra Nevada (Ducea and Saleeby, 1998), and high-temperature metamorphism in the Himalayas (Bird, 1978). Daly (1933) also emphasized the link between major stoping and assimilation/partial melting of continental crust in the broad picture of differentiation of the Earth, a view that hardly differs from modern treatments (e.g., Rudnick, 1995; Jull and Kelemen, 2002; Saleeby et al., 2003; Bédard, 2006).

How should we picture these sinking blocks? If they are eclogite, do we mean simple bimineralic eclogite (transformed basalt), or the full eclogite facies (transformed anything as long as it has dense garnet)? Do we limit ourselves by thinking, for example, that subducted ocean crust can be treated as a single composition, average MORB? Average MORB, after all, is a differentiated rock. How did it get that way?

We have now drilled long sections of lower ocean crust where the full variability of gabbroic differentiation, from olivine-rich troctolite to tonalite/trondhjemite, is juxtaposed by complex high-temperature crystal plastic deformation in every 50-m of the section, and in many 10-m portions of the section (Dick et al., 2000). Based on comparisons to dredge collections, and understanding of tectonic procceses of rift valleys at ridge-transform intersections, this must be typical (e.g., Natland and Dick, 2002). Subduction returns most of this material to the interior of the Earth, and it represents two-thirds or more of the ocean crust. Yet our models of melting relations of subducted ocean crust are based on experiments on single *primitive* compositions of MORB lava. Now we have an additional way of imagining how crustal material enters the convecting mantle, namely delamination, and we are entitled to wonder how far such material might sink and the manner in which it might reappear at the surface of the Earth.

The petrological complexity of the lower ocean crust on so small a scale is important because, even though our knowledge of lower continental crust of Archaean age is limited, that crust surely is no less complicated (e.g., Bédard, 2006). Thus the lower ocean crust universally follows a course of high-iron (Fenner-type) differentiation that leads to formation of oxide gabbro cumulates, which comprise roughly 20% of the average lower crustal section (Dick et al., 2000; Natland and Dick, 2002). Some of these rocks contain up to 30% of magmatic oxides (Bloomer et al., 1991) - ilmenite and titanomagnetite in a ratio of about 5:1 (Natland et al., 1991). These minerals will transform to rutile in the eclogite facies; indeed Alpine eclogite transformed from abyssal

oxide gabbro does indeed contain up to 20% rutile. The parental molten material for these rocks is as close to being a universal Earth magma as any material that exists today. By analogy, we can infer that if voluminous tholeiitic basalt was important to production of continental crust during the Archaean, and especially if, as Bédard (2006) argues, it was emplaced in thick plateaus and was ultimately parental to the widespread tonalite-trondhjemite-granodiorite (TTG) suite of the uppermost crust, then oxide gabbro and/or rutile eclogite was produced along the way. If, for example, the standard depletions in TiO_2, Ta, Y and Nb observed in the TTG suite require separation of one or more titanian phases either as cumulus minerals during crystallization differentiation, or as restite minerals during partial melting, then those minerals are not merely present but abundant in the lower continental crust. The high densities of titanian minerals will also contribute to their tendency to detach and sink into the convecting mantle under appropriate conditions of lower crustal convective instability (i.e., temperatures at or above those of the granulite facies).

Composite intrusive events in an environment of shear characterizes the lower ocean crust at slowly spreading ridges (Dick et al., 2000), juxtaposing all lithologies produced at every stage of differentiation at scales of meters to centimeters. Much of the lower ocean crust thus bears no resemblance to the zoned open-system layered intrusion conceptually based on Skaergaard that is depicted in the standard Penrose ophiolite model (Natland and Dick, 2001). Instead, at slowly spreading ridges, troctolite and olivine gabbro obtained from transform faults are laced with hundreds of seams of oxide gabbro and riddled with tonalite-trondhjemite-granodiorite dikes. Crystal-plastic deformation to form porphyroclastic, gneissic, and mylonitic textures was extensive and occurred at the magmatic stage, probably at temperatures ranging from 700-1000°C (e.g., Natland et al., 1991); many contacts between the different lithologies are along sharp planar shear surfaces. Differentiation was concurrent with deformation. Bédard's (2006) picture of the development of the Archaean lower continental crust by repetitive high-temperature and partly magmatic superposition of one foundered block on top of another differs from this chiefly in scale and occurrence at high pressure, across a high-grade metamorphic isograd.

Foundering of large blocks of Archaean lower continental crust during a later orogenic or rifting event thus will carry all stages of magmatic differentiation recorded by those rocks, and probably also some metasedimentary material, into the convecting mantle. No block of dense gabbro granulite or eclogite will descend without carrying something granitic with it.   The geochemical avatars of "enrichment" will be concentrated in the most strongly differentiated rocks of the subsiding masses – oxide gabbros and proximal tonalite-trondhjemite veins - and by-and-large they will be continental in character. These will contribute to the earliest melt fractions in those blocks as they descend to hotter mantle. Those liquids will likely depart their original hosts because of their buoyancy, and join any streams of basaltic magma that may be ascending from primitive mantle below or around them, modifying their geochemistry, intruding, re-intruding, and intruding again all overlying rocks. If the descending blocks become hot enough, then a low temperature basaltic melt fraction could be produced that is rich in iron and titanium extracted from the oxide gabbros (or rutile eclogite), and this will add to primitive magmas ascending from other sources in the vicinity, producing enrichment in iron and titanium in otherwise primitive compositions. This type of mixing, between primitive and strongly differentiated basaltic magmas, has long been documented along slowly-spreading ridges (e.g., Rhodes and Dungan, 1979; Rhodes et al., 1979), and the mechanism for it – repetitive injection of primitive basalt into deforming rock riddled with seams of incompletely crystallized oxide gabbro – has been discerned in the long sections of gabbro cores obtained by drilling (Natland and Dick, 2002). I propose that this occurs in active flood basalt provinces, but on a glorified scale compared with mid-ocean ridges.

Into what sort of mantle do the sinking blocks of lower continental crust descend? First, they will descend into less dense refractory subcontinental lithosphere, the residual mantle left from extraction of continental crust, and which commonly makes up the roots of Archaean cratons (Jordan, 1979; Gaul et al., 2000; O'Reilly and Griffin, 2006). The refractory character is evidenced by highly magnesian olivine (Fo_{92-94}) and low proportion of clinopyroxene in xenoliths, which are commonly harzburgite. Thicknesses for sub-continental lithosphere beneath Archaean cratons (archons) based on xenoliths are 160-250 km (O'Reilly and Griffin, 2006).   I suggest that low-Ti basalt from

Reykjanes and Kolbeinsey Ridges derives from partial melting of peridotite like this, left behind in the North Atlantic following continental rifting. Physically associated eclogite masses derived from diverse gabbro foundered from lower continental crust, but concentrated beneath Iceland, either add to the volume of melts derived from subcontinental peridotite, or are the only sources of Icelandic basalt.

In the view of Klein and Langmuir (1987), basalt from Reykjanes and Kolbeinsey Ridges represents the low-Na_8, low-Ti_8, high-Fe_8 and high-Si_8 end of the MORB global array (Type 1 MORB in Figure 11). In their melt-column model, such basalt represents partial melting of a homogeneous peridotite source at the highest temperatures and greatest average depths followed by varying degrees of crystallization differentiation, and this has been used to support the plume model for Iceland. The alternative interpretation is that occurrence of such basalt depends on bulk lithologic heterogeneity in the melt source, namely a predominance of relatively refractory and infertile, nearly harzburgitic, peridotite rather than more fertile lherzolite (Jaques and Green, 1980; Natland, 1989; Sweeney et al., 1991; Green et al., 2001; Presnall et al., 2002; Anderson and Natland, 2005; Green and Falloon, 2005). This heterogeneity is, as I believe, provided by continental rifting, which is then the fundamental mechanism for the association of primitive tholeiitic picrite, higher-Ti ferrobasalt, and rhyolite at Iceland, all the geochemical evidence for mixing that I have outlined above, and the contrast between Icelanic tholeiite and the slightly different but nevertheless very distinctive basalt from the adjacent Reykjanes and Kolbeinsey Ridges.

For East Greenland, where volcanism of the North Atlantic igneous province began in the Paleogene, there is no requirement that this type of magma mixing required foundered blocks of lower crustal material. Those rocks were already there. Intact lower continental crust heated by intensive dike injection was subject to *in situ* partial melting of low-temperature gabbroic constituents, which inevitably mixed with ascending magma. However, for basalt erupted later across the North Atlantic and at Iceland, foundered, stoped, peeled off, or otherwise delaminated blocks of lower crust were essential.

To investigate this hypothesis, greater attention to continental xenolith suites in and around flood-basalt provinces, to confirm the presence and petrochemical character

of oxide gabbros or equivalent material in the granulite and eclogite facies, becomes important.   On the other hand, even if such material is rarely found, perhaps because of its efficiency of incorporation into flood basalt, high-Ti basalt such as that at Iceland is very difficult to explain without something like the mechanism proposed here. It does not derive from crystallization differentiation of primitive, low-Ti basalt, nor certainly does affiliated rhyolite. On its own merits, then, the widespread occurrence of high-Ti basalt in continental flood-basalt provinces indicates that the lower reaches of ancient continental crust commonly contain oxide-rich gabbro or its equivalent in the eclogite facies, and in this way supports the plateau model of formation of Archaean continental crust proposed by Bédard (2006) and numerous prior workers whom he cites.

Compared with plumes, theoretical consideration of delamination of continental lithosphere and convective instability of lower continental crust is in its infancy. Perhaps the simplest way to consider it is to view the lithosphere as a thermal boundary layer cooled from the top. In appropriate plate-tectonic circumstances this boundary layer produces instabilities of varying dimensions that allow dense crustal rocks to sink into deeper mantle. In effect, this is the plume hypothesis turned upside down. However, the lithosphere is by no means uniform in its lithologic composition, the distribution of radioactive elements within it (Andreoli et al., 2006), or its responsiveness to thermal or chemical heterogeneity of the convecting asthenosphere over which the plates move. Proterozoic and younger formerly mobile belts separate many Archaean cratons and much continental crust consists of sutured terranes of the remnants of arcs, backarc basins, and accretionary sediment prisms sometimes pinched between collided continents. How and where large concentrations of lower continental crust might subside into the underlying mantle and later re-appear to influence ridge and mid-plate volcanism are open questions that require the insights of geology, geophysics, igneous and metamorphic petrology, and geochemistry to resolve.

CONCLUSIONS

I recapitulate briefly.

1) Closed-system crystallization differentiation of depleted MORB from primitive tholeiite to silicic compositions as differentiated as dacite produces no spread of data points on ΔNb diagrams.

2) Such spread of data points on ΔNb diagrams as exists along the East Pacific Rise results from magma mixing between truly depleted N-MORB at one extreme, E-MORB of alkalic character, at another, and – very slightly – high-SiO_2 dacite-rhyolite produced by shallow differentiation at a third; only mixing with E-MORB causes shifts from negative to positive ΔNb.

3) Consideration of likely mixing end-members points to the existence of an extreme truly depleted MORB, found principally in transform faults and near-axis seamounts, as the principal depleted magma type along the East Pacific Rise; commonly construed N-MORB is a hybrid combining truly depleted MORB (~90%), E-MORB (~5%), and some silicic differentiates (~5%) in axial magma chambers and conduit systems.

4) For Iceland, on the other hand, ΔNb diagrams show a large spread in data points corresponding to the sequence low-Ti tholeiite, high-Ti tholeiite, and silicic differentiates including rhyolite, none of which therefore can be related to each other by closed-system crystallization differentiation in the crust.

5) In all trace-element and isotopic respects, rhyolite at Iceland occupies the place in mixing models formerly attributed to a generalized enriched component in the mantle; in detail, compositions ranging from strongly differentiated higher-Ti ferrobasalt to dacite comprise an aggregate of enriched compositions involved in the mixing.

6) At Iceland, silicic lavas isotopically resemble the formerly construed pervasive mantle component, FOZO; mixing of most depleted Icelandic tholeiite with silicic melts at levels of 5-10% can account for their isotopic variability.

7) Parental TiO_2 (Ti_8) at Iceland varies by a factor of 10, from about 0.4% to 4%; melt-column models involving peridotite cannot explain this.

8) Instead a titanian phase is required in melt sources to explain the most titanian parental compositions, and this in turn entails a gabbroic rather than peridotitic assemblage in melt sources, one containing ilmenite, titanomagnetite, or (in the eclogite facies) rutile.

9) Primitive low-Ti Icelandic picrite, which in many respects is more depleted than primitive MORB, has trace-element attributes indicating a source in olivine gabbro or troctolite, or their eclogitic equivalents, in which concentrations of trace elements and their ratios are specified by compositions of cumulus plagioclase (e.g., high Sr/REE) and clinopyroxene (e.g., very low Zr/Y), in adcumulates with very low proportions of trapped residual melt.

10) Nearly as depleted but still geochemically distinct tholeiite erupts along the Reykjanes and Kolbeinsey Ridges adjacent to Iceland, but the source of these is a refractory peridotite previously inferred to represent the result of extended melt-column (high-T, high-P) melting of a uniform peridotite source beneath spreading ridges.

11) Instead, I prefer that their mantle source was comparatively refractory and depleted to begin with, and that this entails no particularly higher temperature or degree of melting than that of more typical MORB derived elsewhere from more fertile mantle.

12) The thickened Iceland crust in part results from addition of gabbroic/eclogitic components to the melt source that give rise both to low-Ti and higher–Ti Icelandic tholeiite.

13) I propose that convective instability and foundering of lower continental crust into refractory subcontinental lithospheric mantle provides the necessary combination of melt sources to explain the array of volcanic products at Iceland and along the Reykjanes and Kolbeinsey Ridges; and that Paleogene detachment of rigid upper crust and lithosphere from these rocks during continental initial continental rifting in the North Atlantic allowed retention of the necessary assemblages in the modern convecting mantle to explain the geochemistry of current volcanism at Iceland.

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FIGURE CAPTIONS

Figure 1.

A. Chondrite-normalized rare-earth concentrations in basalt from ridge segments on the Pacific-Antarctic East Pacific Rise near the Udintsev and Eltanin Fracture Zones (Data from PetDb, obtained by Yao-Ling Niu). Basalt from major ridge segments (red dots) has slightly concave-downward and quite parallel REE patterns. One basalt from a short intra-transform eruptive center (blue) is more strongly depleted in light REE and one seamount basalt (green), is relatively enriched. The REE pattern of an andesite (half-filled black squares) parallels the group in red, but has a pronounced Eu-anomaly.

B. Nb/Y versus MgNo for samples in A. Symbols are as in A. Nb/Y does not change during shallow crystallization differentiation that causes MgNo to decrease.

C. ΔNb diagram (log-log Zr/Y versus Nb/Y) for the samples of A and B (symbols as in A) compared with fields for other spreading ridges (RR = Reykjanes Ridge ; EPR = East Pacific Rise ; SWIR = Southwest Indian Ridge) as shown in Fitton et al (1997). ΔNb is defined in the text. The line for ΔNb = 0, the Iceland data field and model trends for melts and residues are also from Fitton et al (1997). The model trends assume a homogeneous starting material in the spinel peridotite (S) and garnet peridotite (G) stability fields. Data fields for abyssal gabbros and 735B silicic rocks (diorites, tonalities, trondhjemites) are from Natland and Dick (2002).

D. ΔNb diagram for basaltic glasses from the East Pacific Rise and near-axis seamounts between Siqueiros and Clipperton Fracture Zones (symbol code in diagram), and for the Pacific-Antarctic East Pacific Rise (symbols as in A) are from PetDB. See text for the explanation of the dashed mixing trend. Note the location of E-MORB generally above the line for ΔNb = 0, and other MORB, including truly depleted MORB below the line.

E. Chondrite-normalized rare-earth diagram based on A, showing field-bounded model mixing patterns 1-4 (see text) superimposed.

F. ΔNb diagram showing effects of mixing of truly depleted MORB with 10% E-MORB, 10% andesite and a combination of the two using just data for the Pacific-Antarctic East Pacific Rise depicted in A and B.

Figure 2.

Zr (ppm) versus Nb/Y for A. samples from the Pacific Antarctic East Pacific Rise and seamounts near the superfast portion of the East Pacific Rise; and B. The East Pacific Rise between Siqueiros and Clipperton Fracture Zones. All data are from PetDb. Symbol keys are in each diagram.

Figure 3.

General geochemical relationships of basalt from Iceland and the adjacent Reykjanes and Kolbeinsey Ridges. All data are from GeoRoc and PetDb. Symbol keys are shown in each diagram. Iceland samples are divided into low-Ti and higher-Ti groups as discussed in the text. Picritic samples have MgO ≥ 10%, and are separately indicated by a smaller superimposed yellow dot on the symbols for low-Ti and higher-Ti compositions. Silicic rocks (>55% SiO_2, or <3.5% MgO) are mainly differentiates of higher-Ti basalt, although some are hybrids of basalt and rhyolite.

A. MgO versus TiO_2. The boundary for discerning low-Ti from higher-Ti basalt is based on picritic compositions, but is extrapolated to analyses with <10% MgO based on computation of Ti_8 (low-Ti basalt has Ti_8< 1.4%). On this basis, most glass analyses from Reykjanes and Kolbeinsey Ridges are low-Ti basalt. The diagram also shows two hypothetical mixing trends, one of basalt with rhyolite and one with a representative differentiated higher-Ti basalt. Only a few analyses appear to represent mixing of significant proportions of rhyolite with low-Ti basalt, although mixing with small amounts of rhyolite may be commonplace. Regardless, strict mixing with rhyolite cannot increase TiO_2 content of low-Ti basalt.

B. ΔNb diagram for samples depicted in A, with the same symbols. The line for ΔNb = 0 is indicated. The solid curving line separates most data for low-Ti picrite from Iceland from low-Ti basalt of Reykjanes and Kolbeinsey Ridges. The displacement of low-Ti basalt from Iceland to lower Zr/Y is one indication for involvement of abyssal gabbro from recycled ocean crust in the mantle source (see text for further explanation and references). Short arrows indicate the samples used for mixing calculations in C. The curving arrows among silicic lavas highlight two trends among extended differentiates with somewhat different Nb/Y.

C. ΔNb diagram showing calculated mixing trends (blue and green curves) between samples indicated by arrows in B. Tic marks along the curves indicated 1%, 2%, 5%, 10% and 20% proportions of the silicic mixing component to each of two primitive basalts, one, a low-Ti basalt from Iceland, the other, a low-Ti basalt from Reykjanes Ridge. Data points for high-MgO basalt from Theistareykir (northern Icelandic rift) and Kistufell (central Iceland) volcanoes are plotted for comparison with the model mixing lines.

Figure 4.

Some isotopic systematics of basalts from Iceland and adjacent ridges. A. $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$. B. $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$. C. $^{143}Nd/^{144}Nd$ versus $^{206}Pb/^{204}Pb$. Data are from GeoRoc and the Lamont Petrology Data Base (PetDb) plus some more recently published. Locations of depleted MORB mantle (DMM) and FOZO are from Bell and Tilton (2002). See key for symbol explanations. On all diagrams Icelandic dacites and rhyolites (SiO_2 > 62%) plus other lithologies with $^{87}Sr/^{86}Sr$ > 0.7034 occupy the region of FOZO. Arrows show two possible mixing trends with ends in rhyolite of different isotopic composition that correspond to the two trends among silicic compositions in Figure 3B.

Figure 5.

Some rare-earth-element systematics for Iceland and adjacent ridges. See key for symbols. Data are from GeoRoc and the Lamont Petrology Data Base (PetDb) plus some more recently published. Low-Ti and high-Ti basalts are given the same symbol, as are silicic rocks (>55% SiO_2, or <3.5% MgO), otherwise symbols are based on locations.

A. Chondrite-normalized $[La/Sm]_N$ versus Yb_N. The area with the blue background is blown up in B. Silicic samples OR135 (Örafæjökull) and SNS17 (Snæfellsness) fall in the separate trends for silicic lavas indicated in Figure 3B and 4.

B. Inset of A showing showing calculated mixing trends from two starting basalt compositions with two different rhyolites, samples OR135 (Örafæjökull) and SNS17

(Snæfellsness), in proportions indicated by successive tic marks, 1% 2% 5% 10%, 20% and 50%. The yellow field is that of Schilling (1973a) for the Reykjanes Ridge. His trend for "gabbro fractionation" (= shallow crystallization differentiation of clinopyroxene, plagioclase and olivine) is also indicated.   The trend for, e.g., Theistareykir, is reproduced by 1-5% mixing with rhyolite OR135.

C. $[La/Sm]_N$ versus $^{87}Sr/^{86}Sr$ for Iceland and adjacent ridges. Symbols are as in A. Data for primitive basalt from Theistareykir show a strong correlation between the two ratios and point directly toward rhyolite OR135, although changes in ratios are not proportionally related on this ratio-ratio diagram. At other locations, eg., Snaefellsness, samples with $[La/Sm]_N$ >1 have nearly constant $^{87}Sr/^{86}Sr$ because mixing trends usually curve on ratio-ratio diagrams, depending on the concentrations of the elements or isotopes, and the proportions of mixing.

Figure 6.

The diagrams show results of calculations for potential mixing between primitive depleted tholeiites and both higher-Ti basalt and rhyolite on rare-earths at Iceland.

A. Representative chondrite-normalized REE patterns for Iceland used for mixing calculations and comparisons. Symbols are: gray triangles – basalts with fanning REE patterns from Theistareykir volcano that span the range in $[La/Sm]_N$ for Theistareykir in Figure 5C; black triangles – most depleted non-picritic Theistareykir sample TH9372 used in calculations; half-filled red squares – icelandite and rhyolites with negative Eu-anomalies, including sample R-06, which is used in the calculations; half-filled light blue circles – high-Ti basalt OR134 (Örafæjökull) also used in calculations; plotted for comparison are green triangles – sample Westward 03-21-2, E-MORB; and blue dots – sample Westward 60-02, truly depleted MORB, both from the Pacific-Antarctic East Pacific Rise (also plotted in Figure 1A).

B. Calculated mixing proportions (patterns with red dots) between TH9372 and 1%, 2%, 5%, 10% 20% and 50% of high-Ti basalt OR134. Note the similarity between the 50:50 mixture and E-MORB Westward 03-21-2 from the Pacific-Antarctic East Pacific Rise. The mixing does not result in Eu anomalies. The gray background spans the fanning range of Theistareykir basalts in A. The blue background spans the range of REE in basalt samples from Reykjanes Ridge. These have similar but more restricted fanning patterns, and a limited range at somewhat higher concentrations of heavy REE.

C. Calculated mixing proportions (patterns with blue dots) between TH9372 and rhyolite R-06 in the same proportions as in B. Background fields are as in B. Notice that even small proportions of mixing readily produce negative Eu anomalies.

Figure 7.

MgO versus Nb/Y for Iceland and adjacent Ridges.

A. All data from GeoRoc and PetDb. Symbols are given in the key, and are as in Figure 3A. Since crystallization differentiation does not change Nb/Y, the difference between low-Ti and higher-Ti basalt at Iceland is produced in another way.

B. Curving trends show effects of mixing of different proportions of rhyolite R-06 and high-Ti basalt OR134 with primitive basalt TH9372, as depicted for REE in Figure 6. All data for Theistareykir (gray triangles) are shown for comparison. Most Theistareykir picritic compositions (MgO $\geq$ 10%) have low Nb/Y. Much Theistareykir

basalt with <10% MgO has higher Nb/Y. This indicates that most olivine accumulation among picrites occurs before a change in Nb/Y is superimposed during shallow differentiation; i.e., it is not a signal of mantle heterogeneity. In shallow differentiating magma chambers, then, Nb/Y is increased by mixing with either rhyolite or high-Ti basalt along trends given by the red and blue dots. The spread in data at Theistareykir occurs because of a combination of mixing and shallow fractional crystallization (black arrows). A maximum of about 15% admixture of material similar to high-Ti basalt OR134, or of 5% rhyolite R-06, or some combination of the two with primitive basalt is suggested by the mixing trends. This would steepen rare-earth patterns but produce at most only slight Eu-anomalies in Figure 6C (none in Figure 6B). The full spread in Theystareykir light-REE without significant Eu-anomalies then follows from subsequent shallow crystallization differentiation that drops MgO contents from about 11% in liquids to about 6%.

Figure 8.

A-C) Zr versus Nb/Y and D) versus $^{87}Sr/^{86}Sr$ for Iceland and adjacent ridges. Symbols are given in keys to each diagram. The dashed line divides samples corresponding to the two groups (Group 3 above and Group 2 below the line) of differentiated lavas with differing Nb/Y shown in Figure 3B, different $^{87}Sr/^{86}Sr$ in Figure 4, and different $[La/Sm]_N$ in Figure 5, and is repeated on all diagrams here.

A. Low-Ti basalt, including samples from Kistufell and Theistareykir compared with low-Ti samples from Reykjanes and Kolbeinsey Ridges. Most samples follow curving trends toward higher Nb/Y and Zr concentrations, but level off in Nb/Y at Zr concentrations of about 150 ppm. The curving trends cannot be produced by crystallization differentiation at low or high pressure. Note the offset of Reykjanes and Kolbeinsey samples toward higher Zr than in low-Ti basalt from Iceland.

B). Higher-Ti basalt and differentiates distinguished by composition as given in the key. None of these has low Nb/Y. Differentiates comprise two groups (2 and 3), mostly below and above the dashed line respectively.

C) Mixing calculations between primitive basalt TH9372 and high-Ti basalt OR134 (red curve with % high-Ti basalt indicated at dots) and high-Zr rhyolite HSK-10, with 1050 ppm Zr (blue curve with % rhyolite dots). Samples with 20-50% mixing resemble silicic compositions with 55-65% SiO_2 in B, suggesting that many of those could be hybrid rocks. A data field for abyssal gabbros from ODP Hole 735B (Natland and Dick, 2003) is broken into a) troctolite and olivine gabbro (orange); b) gabbro and disseminated-oxide gabbro (yellow); and c) oxide gabbro (light green). Most primitive Icelandic low-Ti basalt (in A, with Nb/Y = 0.03-0.10) matches olivine gabbro and troctolite in having very low Zr concentrations.

D. Data are broken down partly by location and divided by lines separating Group 1 (depleted Icelandic and Reykjanes-Kolbeinsey tholeiites); Group 2 (values of $^{87}Sr/^{86}Sr$ similar to and including values of higher-Zr silicic differentiates from Snæfellsness), and Group 3 (values of $^{87}Sr/^{86}Sr$ similar to silicic compositions from Örafæjökull.) The complete Örafæjökull field, which spans Groups 2 and 3, is shown with a yellow background.

Figure 9.

Additional trace-element ratios (A-F) and $^{206}Pb/^{204}Pb$ (G) plotted versus Zr/Y. Symbols are given in the legend to A. Data are from GeoRoc.

Figure 10.

Spider diagrams for trace elements comparing compositions of (A) Icelandic picrites with Zr/Y < 1.2 (GeoRoc) with (B) abyssal olivine gabbro and troctolite adcumulates with Zr/Y < 1.2 from ODP Hole 735B, Southwest Indian Ridge (Natland and Dick, 2002, Appendix B). Data are normalized to Hofmann's (1988) primitive mantle composition. Also plotted in A are average Mauna Loa high-Sr glass inclusions (Sobolev et al., 2000), average primitive olivine tholeiite from Kistufell volcano, central Iceland (Breddam, 2000), averages of Group 2 and 3 glass inclusions in Icelandic picrites (Gurenko and Chaussidon, 1995; Sigurdsson et al., 2000; and Slater et al., 2001), and an average of gabbro cumulates from Hess Deep (Pederson et al., 1995, J. Natland, unpublished data).

Figure 11.

Parental characteristics of basalt from Iceland and adjacent ridges. Symbols are given in the keys. Silicic compositions are excluded. The parameters Ti_8, Na_8 and Fe_8 are corrected to the nominal comparative values of 8% MgO both for samples with <10% MgO using formulae of Klein and Langmuir (1987), and for samples with >10% MgO by correction to accumulation of composition Fo_{86}, as described in the text.

A. Fe_8 versus Ti_8. An approximate data field for low-Ti Indian MORB is given by the dashed red circle, and coincides with both low-Ti Icelandic basalt and low-Ti basalt from Reykjanes and Kolbeinsey Ridges. The parallel lines bound remaining Indian MORB. The red arrow gives a general trend for the global MORB array in the Indian Ocean, with decreasing integrated extent of melting in the melt-column models of Klein and Langmuir (1987) and Langmuir et al. (1992) trending toward higher Ti_8 and lower Fe_8. The longer black arrow shows the extent of the "local trend" in the Indian Ocean. Neither the global array nor the MORB local trends match the greater contrast between low-Ti and higher-Ti Icelandic basalt. Discounting the effects of the MORB local trend, many Icelandic basalts have somewhat higher Fe_8 and greatly higher Ti_8 than primitive MORB. Some Iceland basalt with very low Fe_8 could either be hybrids with silicic lava, or rich in plagioclase phenocrysts.

B) Na_8 versus Ti_8. The skewed red box with blue background provides comparison to Indian MORB, with the sequence Type 3 to Type 2 to Type 1 representing subdivisions of the global array, which correspond to increasing extent and average depth of partial melting in the melt-column models of Klein and Langmuir (1987) and Langmuir et al. (1992). Many Icelandic basalts have greatly higher Ti_8 than any MORB, but in the majority of them this is at low Na_8, representing high, not low, extents of partial melting in MORB melting models.
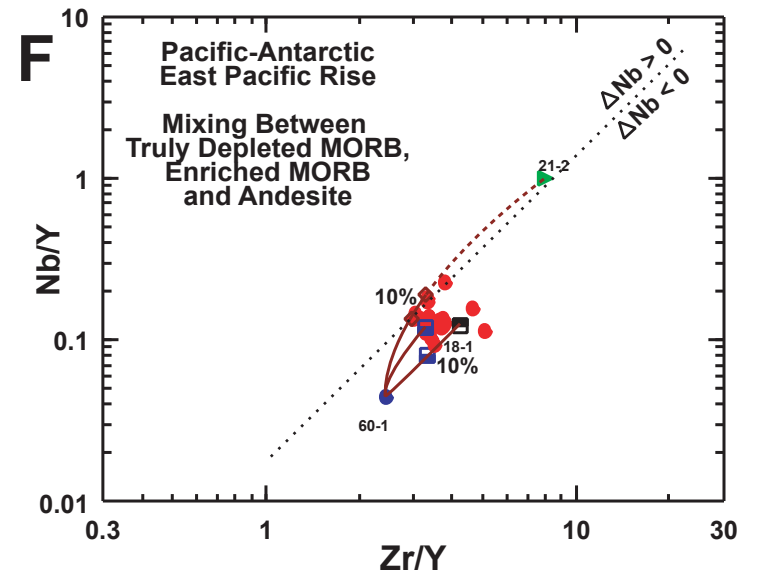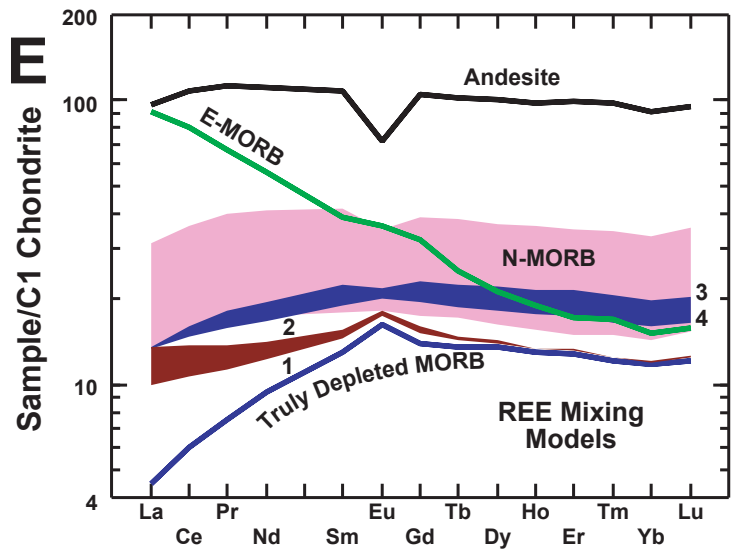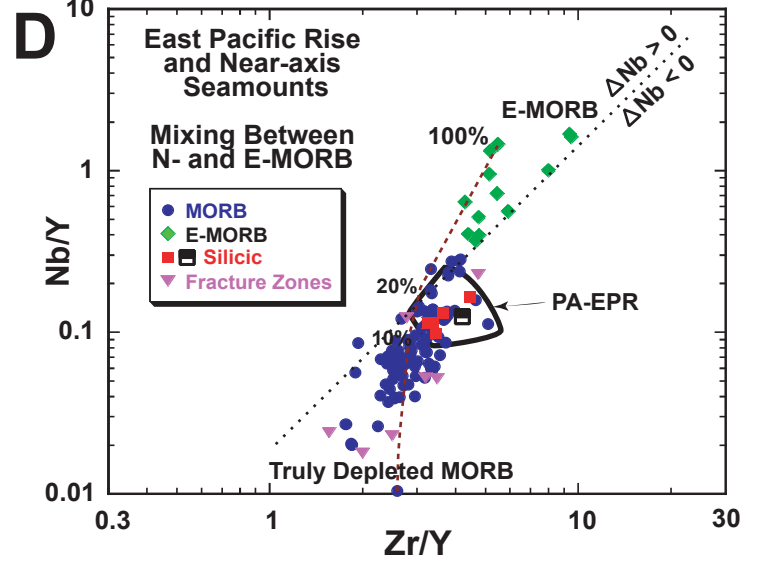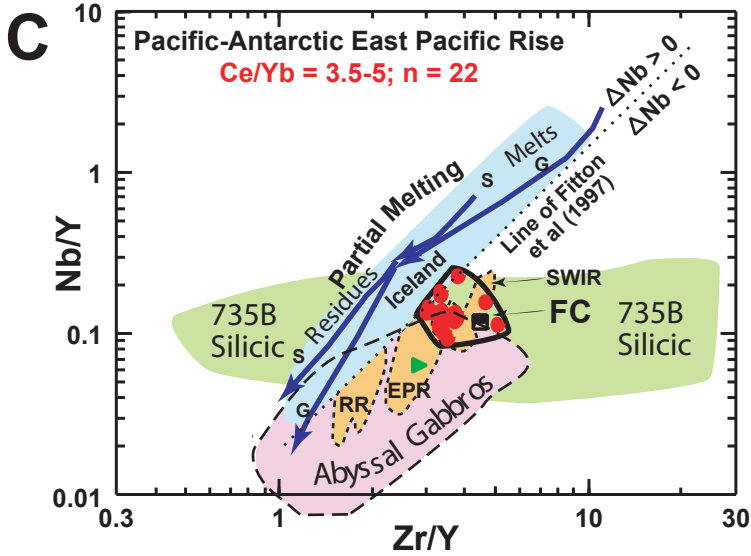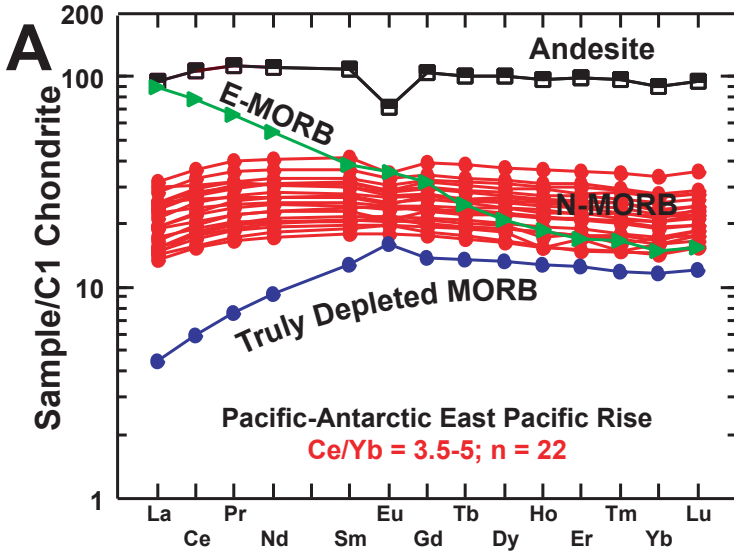
Figure 1
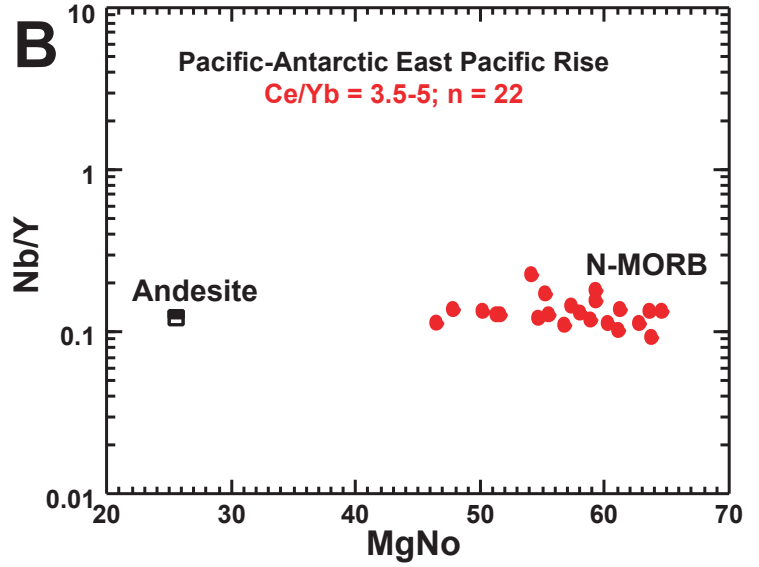
Figure 2

Figure 3

Figure 4

Legend:
- ● Basalts 87Sr/86Sr < 0.7034
- ■ 87Sr/86Sr > 0.7034
- ■ SiO2 > 62%
- ◇ Kolbeinsey and Reykjanes R.
- ▲ Picrites

A — y-axis: $^{143}Nd/^{144}Nd$; x-axis: $^{87}Sr/^{86}Sr$; FOZO

B — y-axis: $^{87}Sr/^{86}Sr$; x-axis: $^{206}Pb/^{204}Pb$; FOZO; DMM
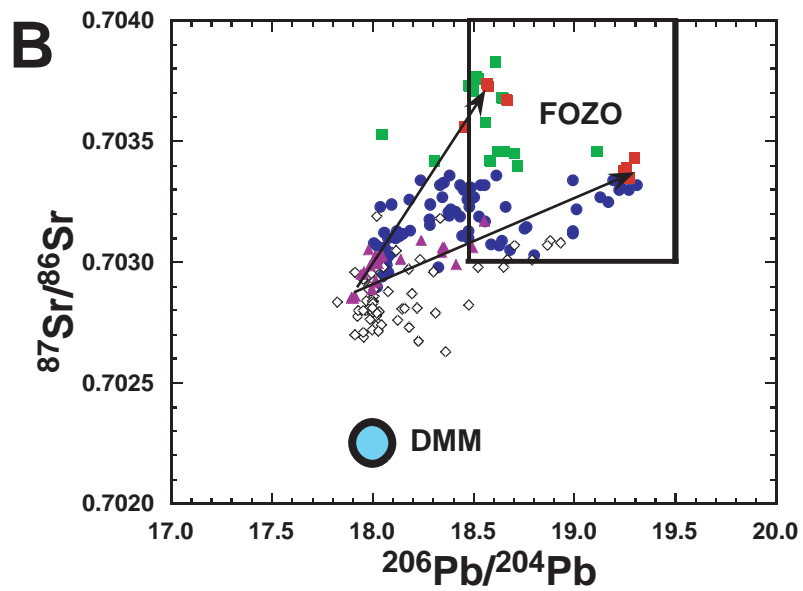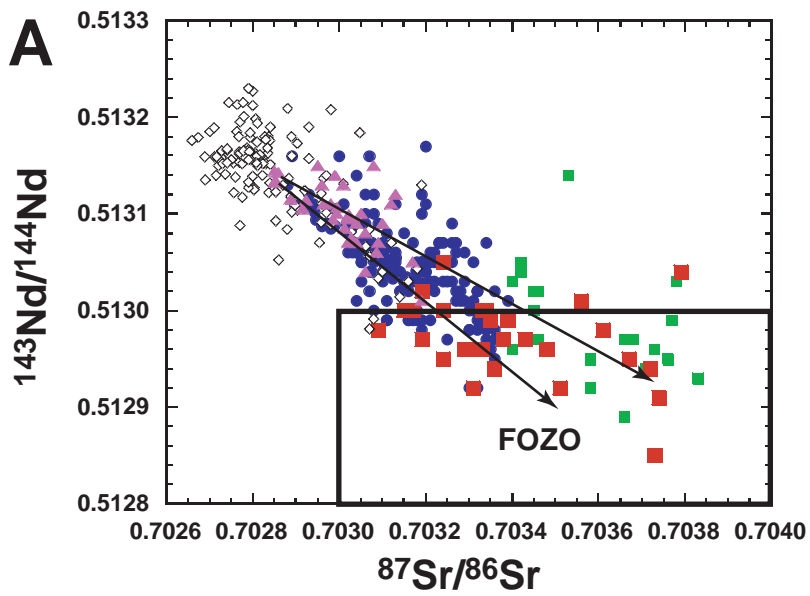
C — y-axis: $^{143}Nd/^{144}Nd$; x-axis: $^{206}Pb/^{204}Pb$; DMM; FOZO
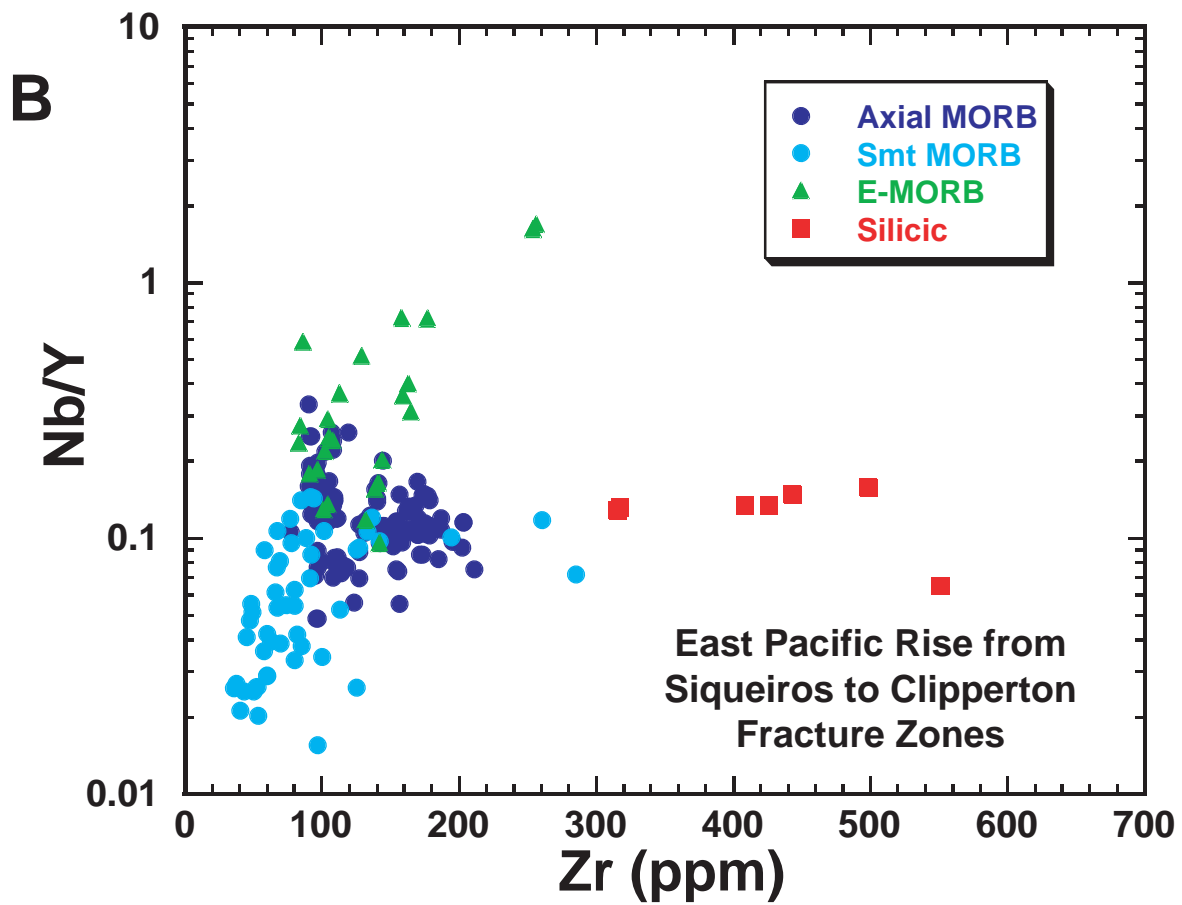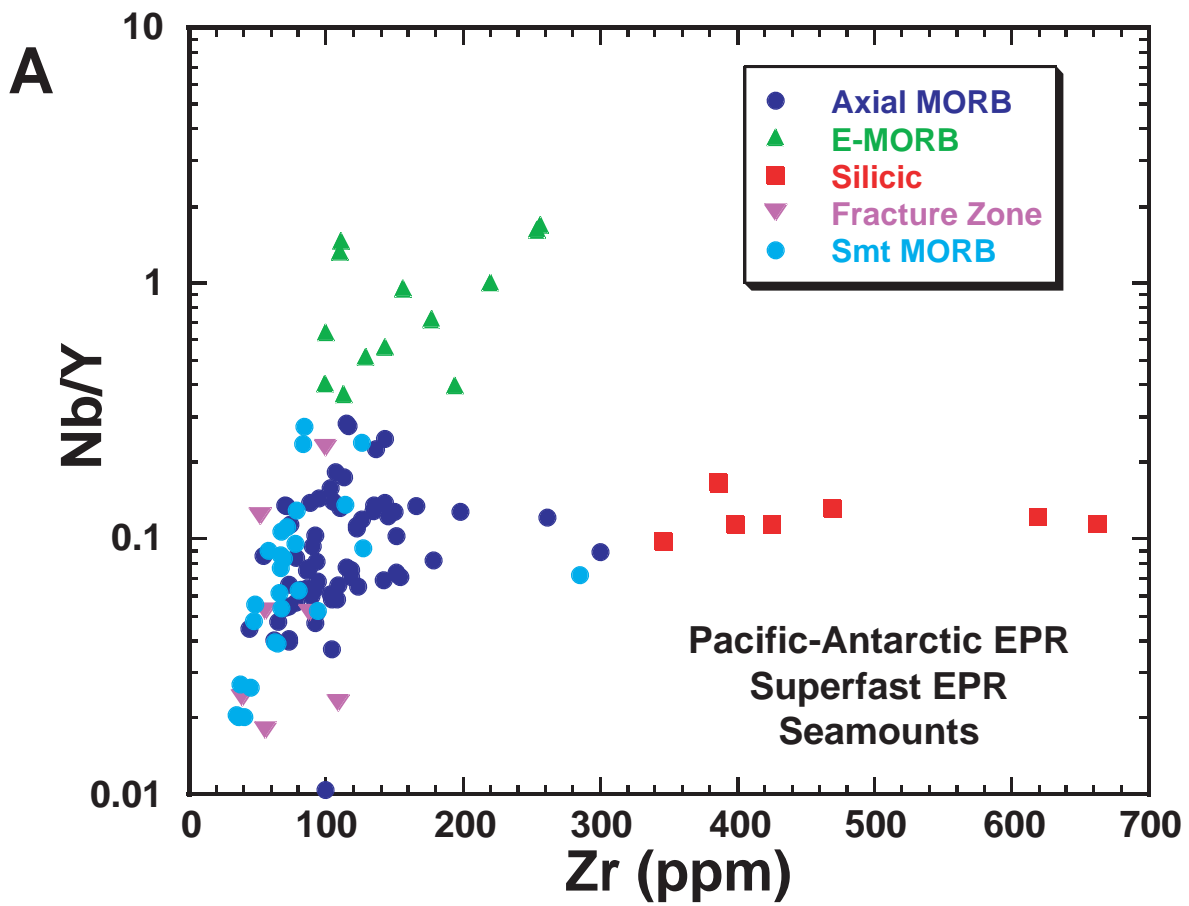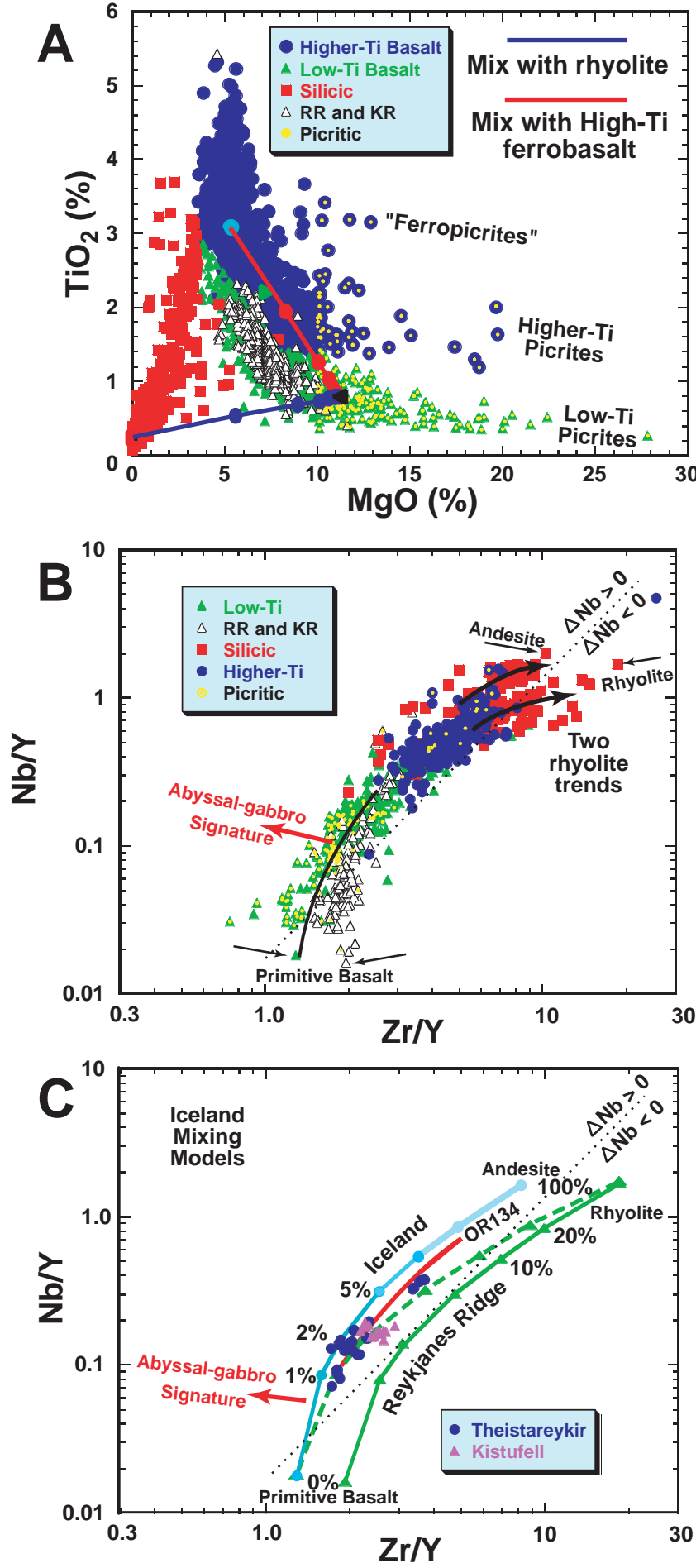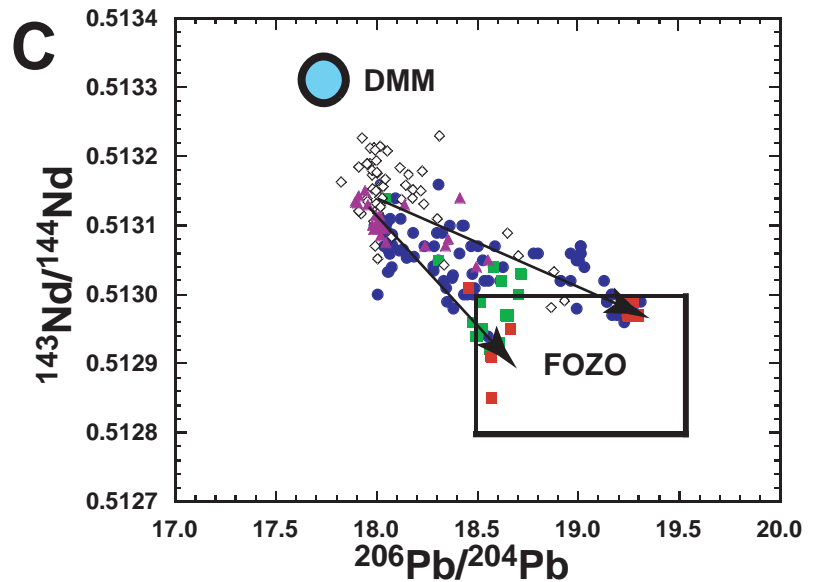
Figure 5

Figure 6

Figure 7

A — Iceland and adjacent Ridges

Legend:
- Low Ti
- RR and KR
- Picritic
- Silicic
- Higher-Ti Basallts

Axes: Nb/Y (vertical), MgO (%) (horizontal)

B — Iceland
Mixing Models Compared To
Theystareykir and Krafla

Legend:
- Mix with rhyolite
- Mix with High-Ti ferrobasalt

Labels: R-06, OR134, TH9372, Fract. Cryst., 50%, 20%, 10%, 5%, 2%, 1%

Axes: Nb/Y (vertical), MgO (%) (horizontal)

Figure 8

Figure 9

Figure 10

A — Iceland Low-Ti Picrite

Mauna Loa ave high-Sr
Ave Kistufell
Hess

3 2
Iceland average
melt inclusions

Normalized to Hofmann (1988)
Primitive Mantle

Ba Nb Sr Nd Sm Ti Y Yb
Th La Ce Zr Eu Dy Er

B — ODP 735B Olivine Gabbro and
Troctolite Adcumulates

Normalized to Hofmann (1988)
Primitive Mantle

Ba Nb Sr Nd Sm Ti Y Yb
Th La Ce Zr Eu Dy Er

Figure 11