What's going on at Iceland?

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Icelandic volcanic rocks present the peculiar geochemical feature that the extent of geochemical enrichment deduced either from trace elements or isotopes, and conventionally attributed to mantle source heterogeneity, correlates with the degree of differentiation of the rocks. Whereas at most other island chains, ranges in extent of depletion or enrichment are grounded in compositions of primitive basaltic lavas (olivine tholeiite, alkalic olivine basalt, basanite, olivine nephelinite) that are interpreted to be little removed in composition from direct and successively smaller partial melts of the mantle, the full isotopic variability at Iceland occurs within tholeiitic basalts and associated differentiates (see **Iceland Petrologic Conundrums Figure 1, below**). Not only this, but the average differentiated basalt, usually a ferrobasalt, is more enriched than primitive olivine tholeiite, and the typical silicic eruptive – usually rhyolite – is often more enriched than ferrobasalt. This should not be the case if, as usually thought, all these lava types belong to a common, shallow, tholeiitic liquid line of descent. Instead, the general case at Iceland appears to be that differentiated lavas are *not* so related to primitive basalt, even at the same eruptive centers, even though almost all belong to tholeiitic magmatic lineages.

Recent geochemical studies also indicate that the most primitive Icelandic tholeiites derive from mantle sources that include recycled ocean crust in their bulk composition (Chauvel et al., 1999; Breddam, 2002). Many of the most nearly picritic Icelandic tholeiites are like this, and have geochemical attributes usually ascribed to a "depleted plume component" in the source region (Fitton et al., 1996; 2003; Kempton et al., 2000). The general notion is that ancient ocean crust descends through the entire mantle following subduction, and then is much later entrained by ascending buoyant material derived from near the core-mantle boundary and transported back up through nearly the entire mantle before contributing to partial melting (Halliday, 2002). Enriched Icelandic basalts thus are derived, ultimately, from different but also deep mantle source components entrained in the plume.

However, based on detailed comparisons to drilled abyssal gabbro (Natland and Dick, 2001; 2002) and the variability of basalt compositions along other spreading ridges, I now propose instead that almost all Icelandic volcanic rocks are derived by differing extents of partial melting of eclogite derived from lithologically variable recycled ocean crust that includes basalts, dikes and abyssal plutonic rocks as diverse as troctolite, olivine gabbro, gabbronorite, oxide ferrogabbro, and trondhjemite. Icelandic picrites are derived in the main by large-scale or even entire remelting of abyssal gabbro cumulates, and thus have higher Nb/Zr, Nb/Y, and Nb/U than typical MORB, but MgO contents of <12%, a value typical of abyssal olivine gabbro; ferrobasalts are derived from less extensive melting that selectively extracts constituents of oxide gabbro and gabbronorite from the recycled crustal assemblage; silicic rocks are comparable to the small-degree partial melts of eclogite that have been produced in experimental studies and to tonalite/trondhjemite veins in abyssal gabbros. Alternatively, they may have been produced by extended crystallization differentiation in the thick Icelandic crust, by low-pressure silicate liquid immiscibility, or by partial fusion of varieties of old, deep continental crust stranded in small masses beneath Iceland. Wherever these silicic materials are in the crust or upper mantle, their high concentrations of, e.g., Rb, Th, and U, predict local radiogenic ingrowth that is preferentially extracted and concentrated in small-degree partial melts. Consequently, rhyolite occupies the position of the geochemically most-enriched volcanic material at Iceland, having Sr-, Nd-, and Pb isotopic characteristics elsewhere assigned either to a FOZO or a HiMu mantle component (**see Iceland Petrologic Conundrums, Figure 2, below**). Mixing with or selective assimilation of rhyolite by primitive basalt, which is well documented in many field associations on Iceland, accounts for the variable degrees of enrichment of the basalts. Taking into account the effects of mixing with rhyolite, the residual isotopic heterogeneity of Icelandic basalts is little different from, and no greater than, that of typical basaltic associations combining N- and E-MORB elsewhere along spreading ridges. On the East Pacific Rise between Clipperton and Siqueiros Fracture Zones, E-MORB (K_2O = 0.5-1.1%) comprises about 6% of basalt erupted both along the ridge axis and on nearby seamounts (based on analyses in the Lamont Petrology Data Base), thus should be present in a similar proportion in both extrusive and intrusive portions of subducted masses of ocean crust. Preferential extraction of such material transformed to eclogite may explain some of the general isotopic and trace-element enrichments of Icelandic basalt compared with typical depleted MORB.

Most basalt of Reykjanes and Kolbeinsey Ridges, respectively south and north of Iceland, has parental characteristics (low Na_8, low Ti_8, high Fe_8) indicating greater extents of partial melting of mantle peridotite than that of typical MORB. A difficulty is that Icelandic basalts themselves have *higher* average Na_8 than those of the adjacent submarine ridges (**see Iceland Petrologic Conundrums, Figure 3, below**), something not predicted by melt-column models for a place with thicker crust but the same mantle materials beneath. The low Na_8, Ti_8, and generally low incompatible trace-element concentrations of basalts from Reykjanes and Kolbeinsey Ridges alternatively suggest partial melting of a more refractory (more nearly harzburgitic) mantle source than for typical MORB. Concentrations of incompatible trace elements and isotopic compositions shift gradationally toward Icelandic compositions as the ridges shoal near Iceland, indicating transitions in both directions from predominantly peridotitic to predominantly eclogitic source materials.

Following Foulger et al (2002 and in press), a source for Icelandic basalts in ocean crust of Caledonian age trapped in the Iapetus suture and since re-exposed by continental rifting can account for all of the principal petrologic and geochemical variability of Icelandic volcanic rocks, and their non-exceptional eruptive temperatures, without recourse to a deep mantle plume. Both higher average extents of melting of such readily fused material compared with peridotite, and the steep dip of the crustal material in the fossil suture contribute to the thicker crust at Iceland than elsewhere along the Mid-Atlantic Ridge. The sutured eclogite was trapped between two continental Archaean cratonic keels, the mantle of which is characterized by more refractory peridotite than that beneath most spreading ridges. Detached or abandoned remnants of this ancient peridotite are what now contribute to the distinctive petrologic characteristics of basalts from Reykjanes and Kolbeinsey Ridges, including their relatively high $^3He/^4He$ ratios (R_A =10-15). Even higher $^3He/^4He$ among some (not all) primitive Icelandic tholeiites does not correlate with other isotopic or trace-element attributes of those basalts, thus it is not tied to basalt-rhyolite mixing. Its origin remains enigmatic, but it may derive from rupture of fluid inclusions in olivine-rich cumulates (cf. Natland, 2003) present either in the recycled eclogitic crust, its adjacent trapped abyssal peridotite, or more likely the ancient cratonic mantle that enclosed these rocks from both sides. The high R_A is indicative of the age of lithospheric dunite, not a deep mantle reservoir. The mantle source beneath Iceland is zoned, but not because of a plume.

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Icelandic Petrologic Conundrums
Figures

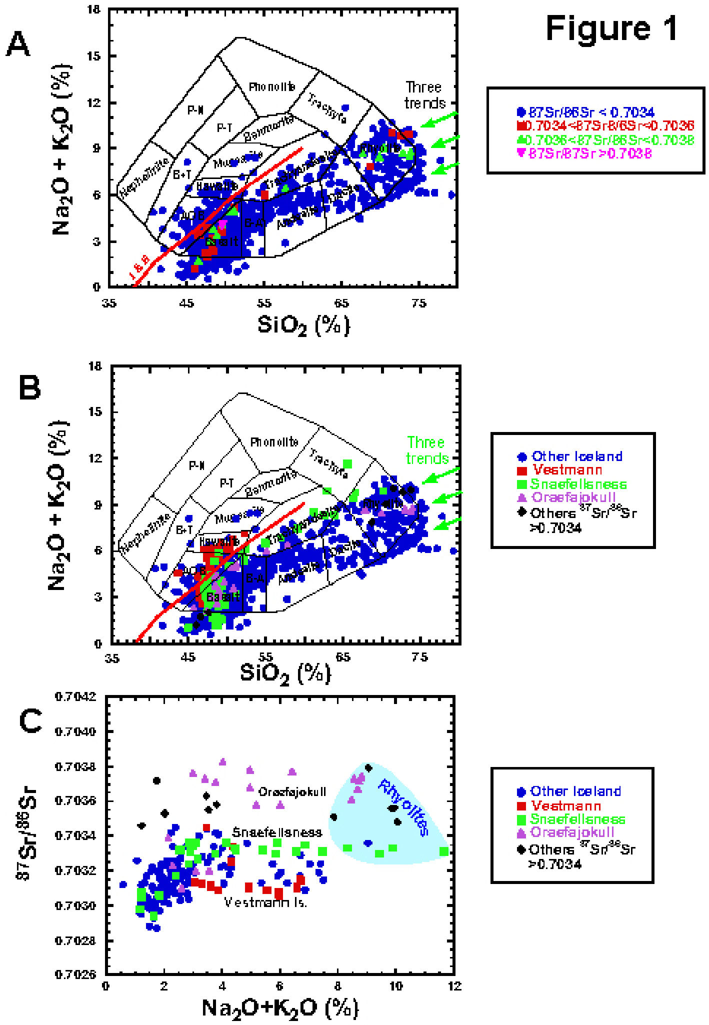

Figure 1

Conundrum 1: *The isotopically most enriched lavas from Iceland belong mainly to tholeiitic, not alkalic, differentiation sequences, and the most enriched of all are rhyolites.*

A. Alkalis-silica classification diagram (Cox et al., 1979) for Icelandic lavas compiled from the GeoRoc data base, plus more recently published data. The transition line of Irvine and Baragar (1971) between alkalic basalts (plotting above the line) and tholeiites (plotting below) is in red. Almost all rocks are tholeiitic-series basalts and differentiates. Samples for which $^{87}Sr/^{86}Sr$ has been measured are shown with different colors, as given in the key. Almost all, including those with highest $^{87}Sr/^{86}Sr$, are tholeiites.

B. alkalis-silica diagram for the same Icelandic lavas plotted in A but with data for mildly alkalic off-axis locales (Vestmann Islands, Snaefellsness, and Oraefajokull) shown using different colors, as given in the key. Although most basalts from these places are mildly more alkalic than from elsewhere in Iceland, they include some tholeiites.

C. Total alkalis versus $^{87}Sr/^{86}Sr$ showing that samples with highest $^{87}Sr/^{86}Sr$ are rhyolites and intermediate lavas with high total alkalis, whereas tholeiitic basalts (mainly with $Na_2O + K_2O$ <4%). The most enriched lavas from off-axis localities, indicated in the key, are intermediate differentiates and rhyolites. Note the consistent yet distinctive isotopic values for each off-axis locale.

Interpretation*. Intermediate compositions are basalt-rhyolite hybrids, and are dominated by the isotopic signature of rhyolite. Mixing, documented by many workers, occurs in the shallow Icelandic crust.*

More primitive basalts are variably contaminated with rhyolite, thus their MANTLE isotopic signature is probably restricted to values of $^{87}Sr/^{86}Sr$ below those of the Vestmann Islands (<-0.7031), and may be no higher than for typical MORB.

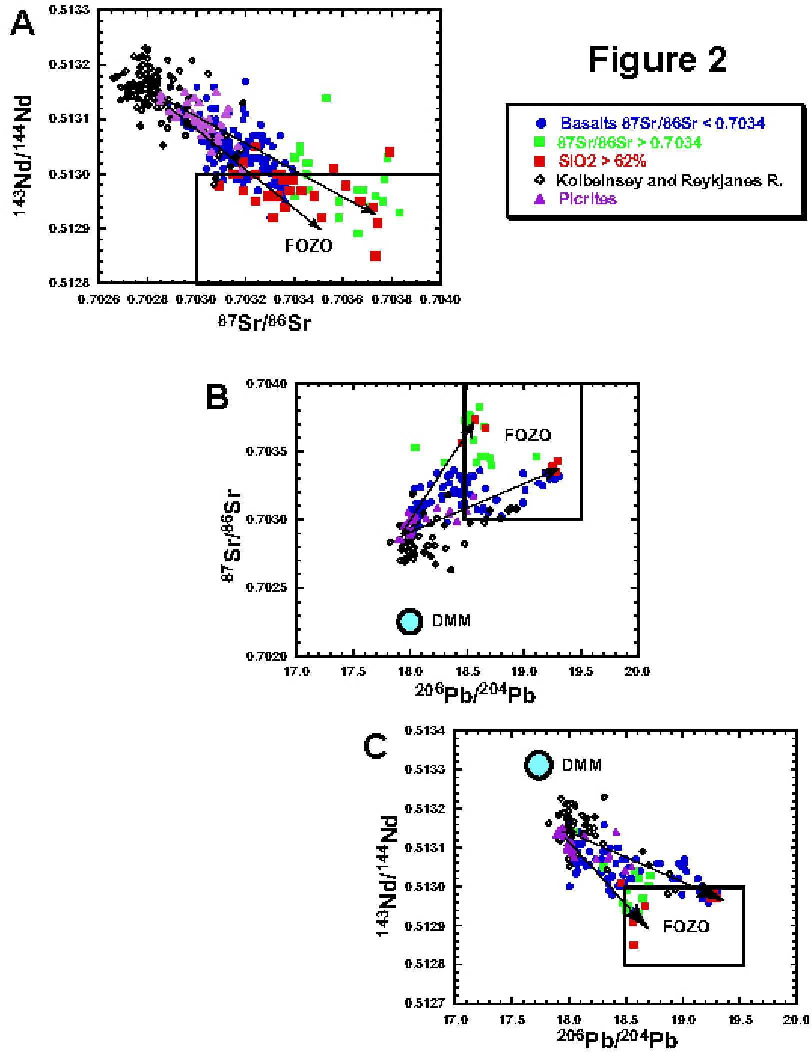

Figure 2.

Conundrum 2. *The "enriched component" at Iceland, with FOZO characteristics, is rhyolite and rhyolite-contaminated basalt, not primitive mantle-derived basalt.*

Some isotopic systematics of basalts from Iceland, Reykjanes Ridge and Kolbeinsey Ridge. 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 keys 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.

Interpretation. *Icelandic basalts and many from Reykjanes and Kolbeinsey Ridges fall mainly along two potential mixing lines (with arrows) between rhyolite and Icelandic picrite, the least contaminated among the latter having isotopic values approaching those of depleted N-MORB.*

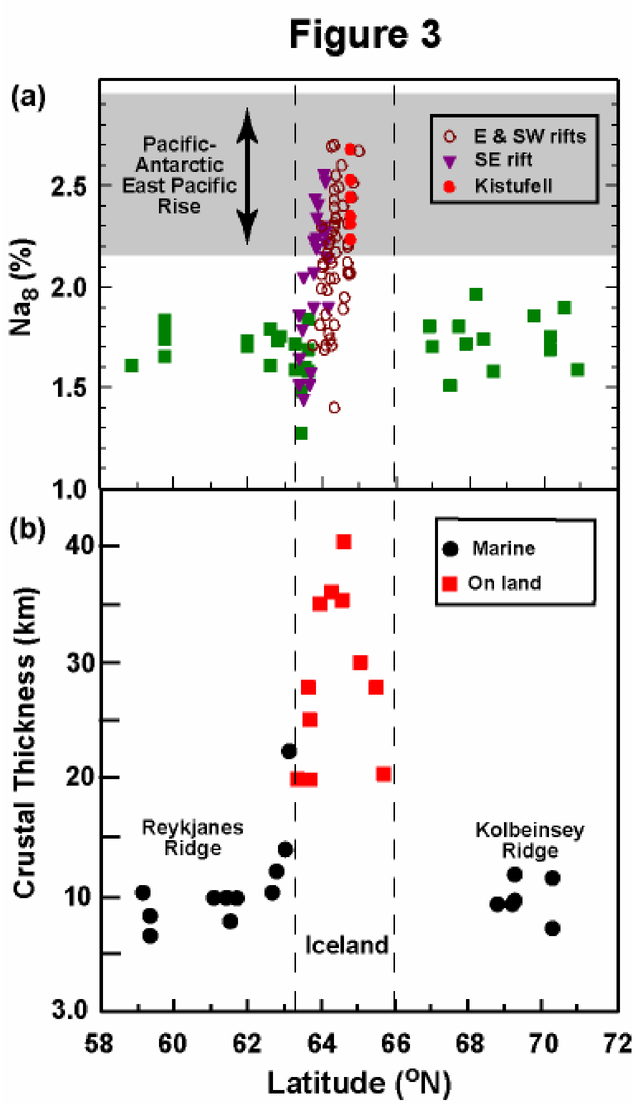

Figure 3

Conundrum 3. *Melt-column models (e.g., Klein and Langmuir, 1987; Langmuir et al., 1992) inversely correlate* Na_8 *with crustal thickness. Iceland contradicts this. Values of* Na_8 *diverge at Iceland from those of adjacent ridges, but on the average increase, precisely where crustal thickness most sharply increases beneath the northern and southern Iceland margins.*

(a) From Foulger et al (ms). Parental soda (Na_8) in basalt glass v. latitude. Data from Kolbeinsey and Reykjanes Ridges (green squares) are from the Lamont petrological database (PetDB). Icelandic compositions (see key) are from Breddam (2002) and Meyer et al. (1985). The range for the Pacific-Antarctic East Pacific Rise is from Castillo et al. (1998). (b) Crustal thickness vs. latitude, with data from a compilation of seismic experiments in Iceland and the North Atlantic.

Interpretation. *Melt-column models invoking a homogeneous mantle source do not apply to Iceland. The mantle source is significantly more fertile with respect to a basaltic melt fraction beneath Iceland than beneath the adjoining ridges. The model suggested by Foulger et al (ms) is that the extra crustal thickness is provided by extensive melting of basaltic and gabbroic ocean crust that was once caught in the Caledonian suture, which persists beneath Iceland in the eclogite facies. Refractory peridotitic sources probably including material once in subcontinental lithosphere supply most of the parental basaltic magma beneath Reykjanes and Kolbeinsey Ridges.*