Origin of the Iceland hotspot and the North Atlantic Igneous Province

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Introduction

To understand the origin of the Iceland hotspot, we must look at the big picture and start from the continental-breakup magmatism that took place during the opening of the North Atlantic around 60 million years ago. Because of spatial and temporal continuity in anomalous magmatic activity, underlying mechanisms for the Iceland hotspot and the North Atlantic igneous province must be closely connected, if not the same.

We may also look at an even bigger picture (Figure 1). The North Atlantic is not the only place where massive breakup magmatism occurred. Large igneous provinces on a similar scale were also created during the opening of the Central Atlantic (the US East Coast igneous province formed at ~200 Ma) as well as the South Atlantic (the Paraná and Etendeka flood basalt provinces formed at ~120 Ma) (Editor's note: see also the Central Atlantic Magmatic Province and South Atlantic pages).

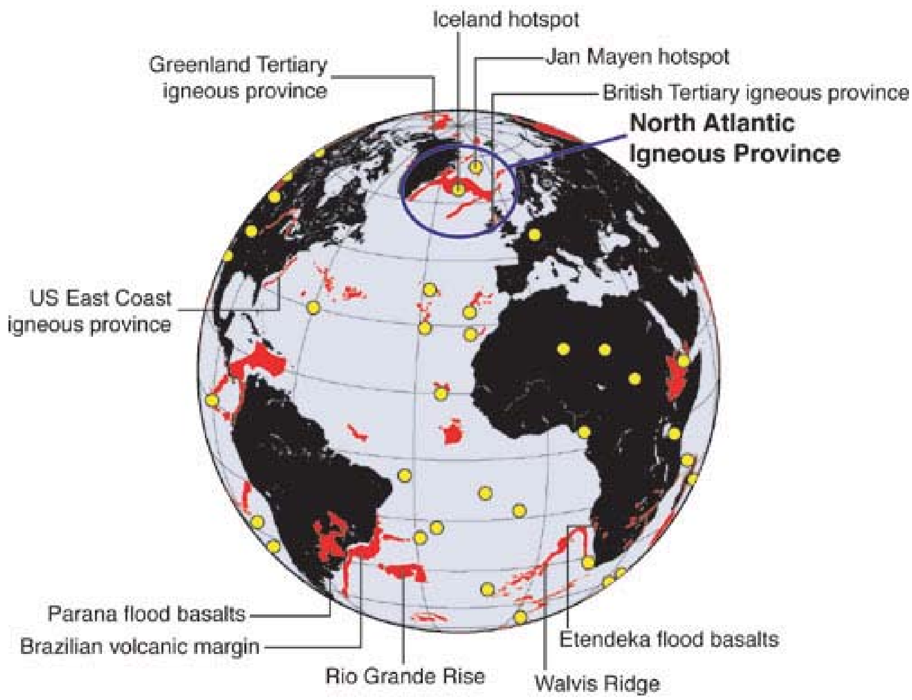


Figure 1. *Most Atlantic large igneous provinces are related to the dispersal of the supercontinent Pangea, which initiated ~200 million years ago. Red areas denote the distribution of large igneous provinces that have been recognized so far, and yellow circles denote currently active hotspots (after Coffin & Eldholm [1994] and Schilling [1985]).*

This rather frequent formation of large igneous provinces during the disintegration of the supercontinent Pangea is a surface manifestation of the thermal and chemical state of convecting mantle beneath the supercontinent. Something unusual (with respect to normal convecting mantle) is required, otherwise normal seafloor spreading would have taken place. The impact of a starting mantle plume (Figure 2) has been a popular hypothesis for the last decade or so, but recent geochemical and geophysical findings from the North Atlantic igneous province all point to the significant role of incomplete mantle mixing in igneous petrogenesis.

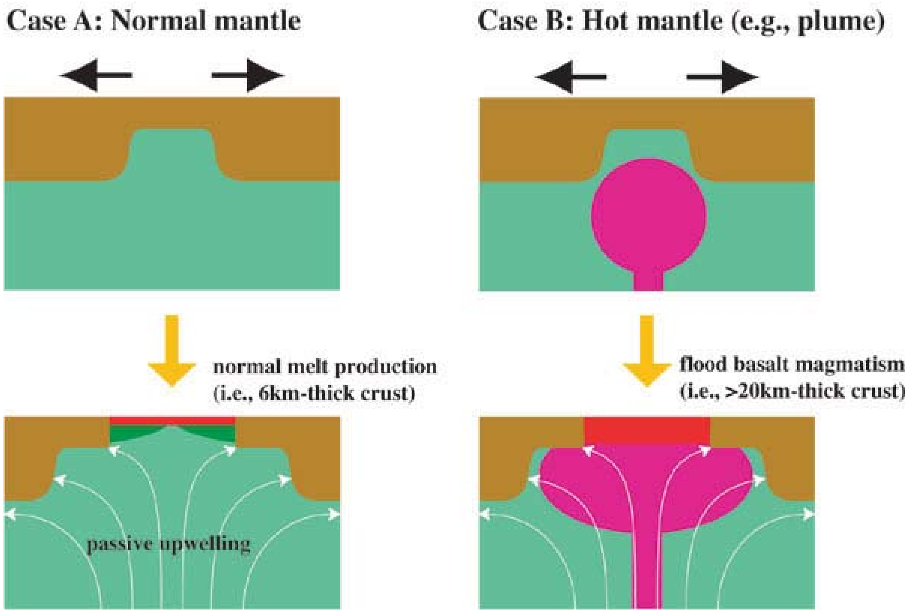


Figure 2. *The most popular hypothesis for continental breakup magmatism is the arrival of a mantle plume. The plume impact hypothesis is a theory that attributes anomalous mantle melting to thermal anomalies in convecting mantle. For the melting of such hotter-than-normal mantle, we can make various geophysical and geochemical predictions, which can be compared with observations to validate the hypothesis.*

In this essay, I first summarize key observational constraints on the nature of parental mantle dynamics for continental breakup magmatism. Available evidence appears to favor a hypothesis in which anomalous magmatism results from fertile mantle, not from anomalously hot mantle. However, this hypothesis has an often-neglected dynamical issue – fertile mantle without a thermal anomaly is denser than normal mantle and it should sink instead of rise, as O'Hara pointed out in 1975. I will show that this dynamical dilemma can be resolved quite naturally if the multi-scale nature of mantle convection is properly taken into account. Multi-scale mantle mixing could potentially explain a variety of hotspot phenomenology as well as the formation of both volcanic and non-volcanic rifted margins, with a spatially- and temporally-varying distribution of fertile mantle.

Observation 1: Mantle Tomography

Both *S*-wave and *P*-wave global tomography models clearly show that a strong low-velocity anomaly beneath Iceland ends sharply at the 660-km discontinuity. It is important to note that this shallow feature of the Iceland low velocity anomaly is supported by *both* *S*-wave and *P*-wave models. *S*-wave models are mainly constrained by surface waves (which are sensitive only to upper mantle structure) and body waves (which have good resolution only for the lower mantle in case of Iceland). The continuity of low-velocity structure might be influenced by how one weights these different data sets in tomographic inversions. The new finite-frequency *P*-wave tomography models of the Princeton group (which benefit from more resolving power for a given ray coverage) provide strong confirmation for earlier *S*-wave models for the Iceland hotspot, in this respect.

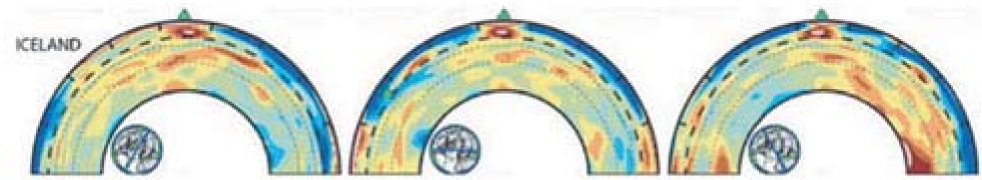


Figure 3. *Global S-wave mantle tomography by J. Ritsema and coworkers (Model S20RTS: the so-called "Caltech model"). Cross sections beneath Iceland sliced at three different angles are shown [from Ritsema & Allen, 2003]. This model is derived from free-oscillation splitting, surface-wave dispersion, and body-wave traveltime measurements.*

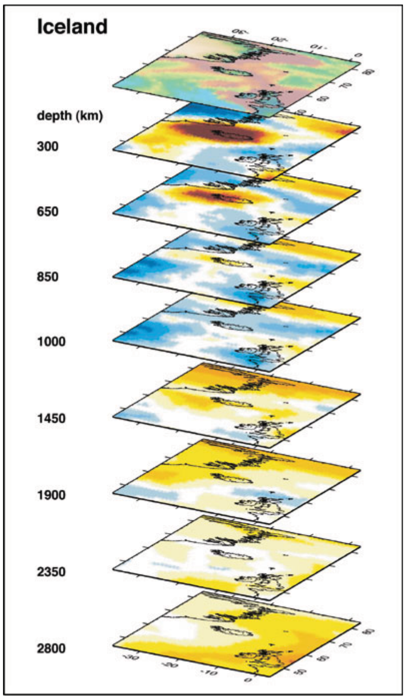


Figure 4. *Global P-wave mantle tomography by Montelli et al. [2004] (the "Princeton model"), based on P and PP traveltimes measured at two different frequencies.*

Observation 2: Crustal Tomography

Melting of hot plume mantle is also irreconcilable with the crustal structure of the Greenland Tertiary igneous province. Hotter mantle produces a larger amount of melt, with increasing MgO content (because of a larger olivine component in the melt). Roughly speaking, the seismic velocity of igneous crust is mainly controlled by this MgO content. Higher MgO leads to higher crustal seismic velocity. Therefore, there should be a *positive* correlation between crustal volume and crustal velocity, if thick igneous crust is produced by melting anomalously hot mantle. This is not observed on the Greenland margin part of the North Atlantic igneous province (Figure 5). Clearly, something other than the melting of hot mantle is involved. Crustal structure alone does not tell us what this is, exactly, so we need to consider complementary information such as mantle geochemistry.

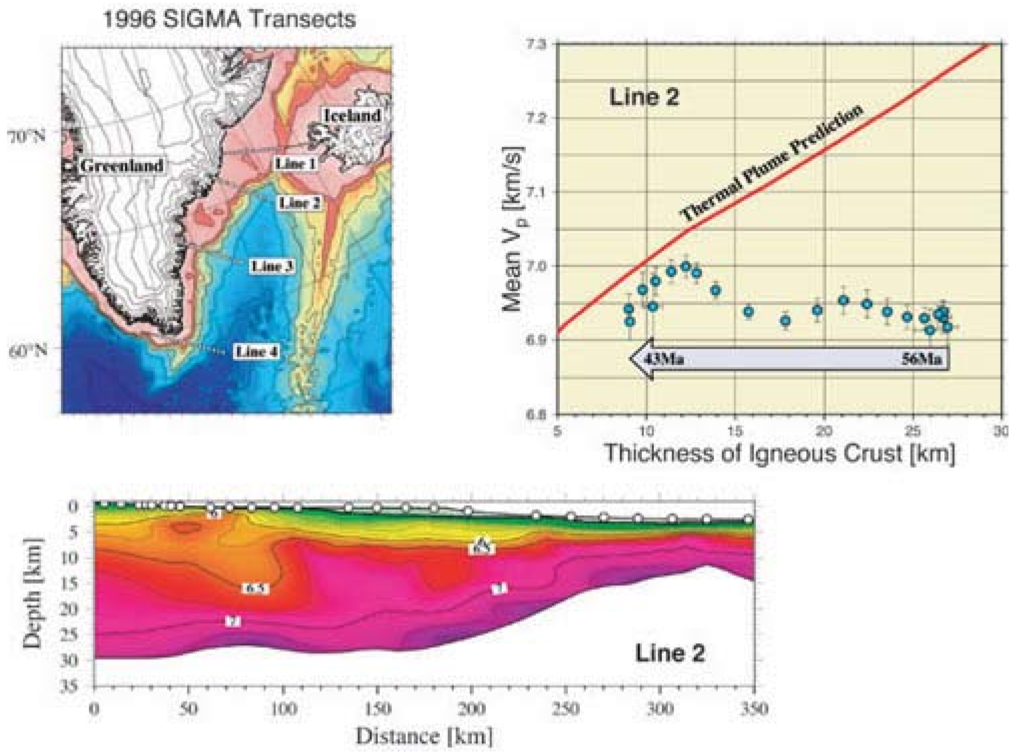


Figure 5. (upper left) *Seismic transects across the southeast Greenland margin surveyed during the 1996 SIGMA experiment by WHOI and DLC [Holbrook et al., 2001]. So far, only Line 2 has been modeled by a tomographic method. Preliminary modeling of the other three transects by (semi-)forward modeling has been published, pendin a more complete tomographic study with proper quantification of model reliability.* ***(upper right)*** *Correlation between P-wave velocity and thickness as seen in the Line 2 crustal model (blue dots with error bars; excluding the contribution from the continental crust component). Red line denotes a theoretical prediction for the case of a thermal plume (see Korenaga et al. [2002] for details.)* ***(bottom)*** *P-wave velocity model for Line 2. For technical details on the tomographic method, see Korenaga et al. [2000].*

Observation 3: Major Element Chemistry

Primary melt compositions estimated for the North Atlantic igneous province suggest that (1) the source mantle is fertile (i.e., Mg#~86-87) probably resulting from the addition of recycled crust and (2) the source mantle is not notably hot with respect to MORB source mantle [*Korenaga & Kelemen*, 2000]. It should be noted that estimating primary melt composition is not an easy task. Surface lava composition is usually very different from primary melt because of various fractionation processes. How do we get something like Figure 6?

Korenaga & Kelemen [2000] devised a fractionation-correction method based on liquid Ni concentration. Ni is only a *compatible* trace element for olivine, which is the most abundant phase in the upper mantle. Thus, the Ni content in mantle olivine is expected to be stable in the face of any previous depletion and enrichment history. Indeed, compilation of mantle xenoliths and abyssal peridotite demonstrates that the Ni content clusters tightly between 2500 ppm and 3500 ppm. We can safely use this range as a reference when we apply back-fractionation correction to surface lava data.

This Ni-based fractionation correction is not a new idea. It had already been proposed, for example, by *Allegre et al.* [1977]. However, we now have much better control on Ni partitioning between olivine and basaltic melt from a large number of laboratory data, and also the distribution of Ni content in mantle olivine is better understood. Furthermore, the correction method is only applicable to relatively primitive samples (with MgO content greater than ~9 wt%). The North Atlantic igneous province is, fortunately, one of the best studied areas in terms of petrology, and the number of suitable samples is sufficiently large.

To test if this revived estimation method really works, *Korenaga & Kelemen* [2000] first applied it to normal mid-ocean ridges. Estimated primary compositions all cluster around the composition space in equilibrium with source mantle of Mg#~0.89, which is a pyrolitic value (see yellow patches in Figure 6). Furthermore, the Indian Ridge, Northern EPR, and the Kolbeinsey Ridge extend most of the “global trend” of mid-ocean ridge basalt composition [*Klein & Langmuir*, 1987]. As shown in Figure 6, inferred melt temperature increases from the Indian Ridge (including the Australia-Antarctica Discordance) to the Kolbeinsey Ridge (referred to as “Iceland” in the complilation of *Klein & Langmuir* [1987]), consistent with expected temperature variations along the mid-ocean ridge system.

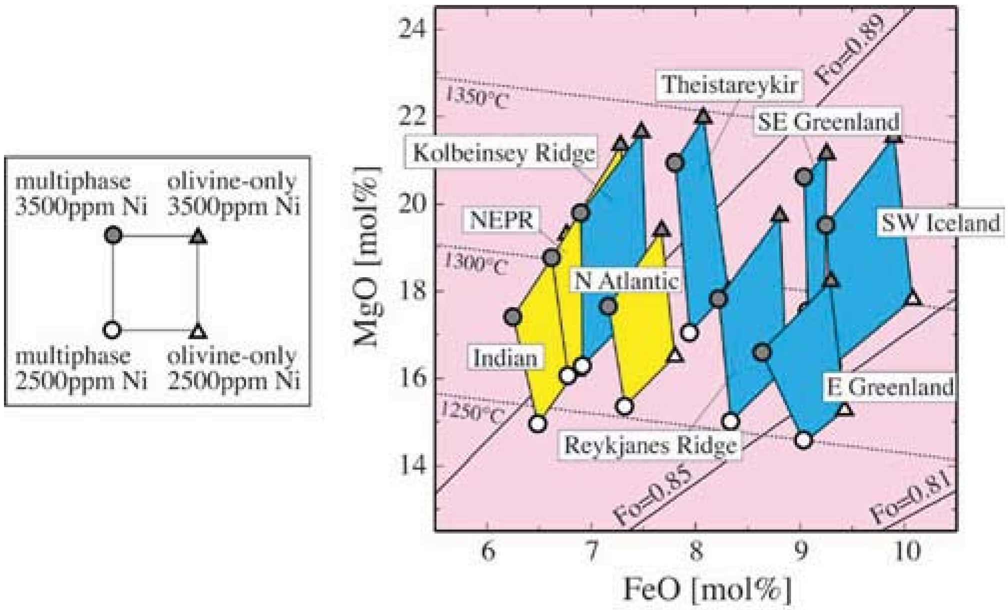


Figure 6. *Estimated primary melt compositions in terms of MgO and FeO for the North Atlantic igneous province (East Greenland, Southeast Greenland, Southwest Iceland, Theistareykir (North Iceland), Reykjanes Ridge, and Kolbeinsey Ridge) and normal mid-ocean ridges (Northern EPR, North Atlantic, and Indian Ridge). Also shown are the contours of melt temperature (dotted) and corresponding Mg# of source mantle (solid). See Figure 7 for how to interpret this primary composition. (From Korenaga & Kelemen, 2000)*

By looking at primary melt compositions for the North Atlantic igneous province, one notices that, whereas the Kolbeinsey Ridge and Theistareykir appear to be similar to normal mid-ocean ridges, other localities exhibit a distinctly different trend with much lower Mg#. This distribution is not random. The Kolbeinsey Ridge is located north of Theistareykir, and they are geographically connected. There appears to be some kind of compositional dichotomy in the source mantle for this igneous province. At any rate, the bulk of the North Atlantic igneous province is characterized by unusually low Mg#, i.e., more iron-rich source mantle, which is more prone to melting because of its lower solidus. In addition, the temperature of the primary melt is not very different from normal mid-ocean ridges (Figure 7). (Note: Do not confuse the temperature of primary melt with the temperature of erupted lava, which does not have a direct connection with the potential temperature of the source mantle.)

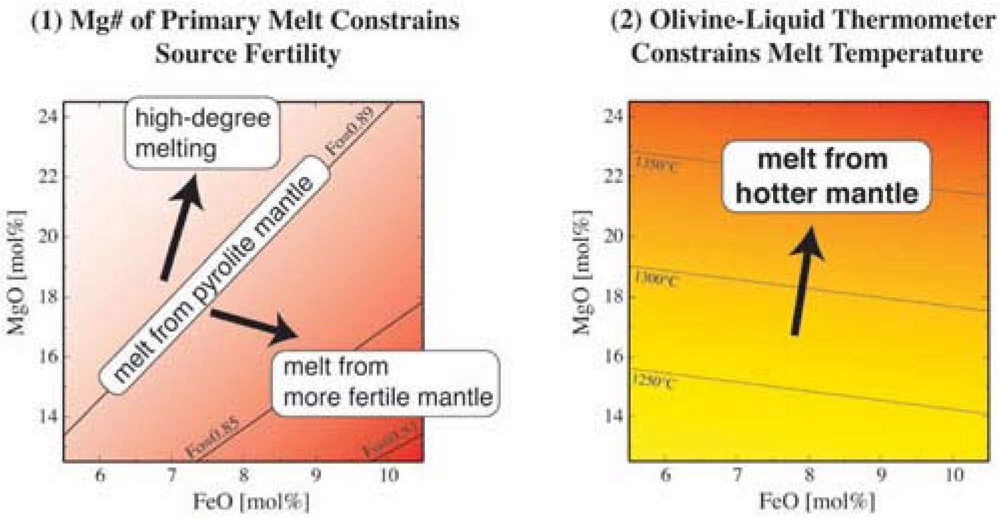


Figure 7. *Primary melt composition in MgO-FeO space tells us two things. (1) Mg# constrains the fertility of the source mantle. Any melt from pyrolite (i.e., normal) mantle has equilibrium olivine Mg# greater than ~0.89. To create melt with a lower Mg#, the source mantle composition must have lower Mg#. (2) Mg-Fe partitioning between olivine and basaltic melt is sensitive to temperature, so one can convert melt composition into melt temperature. By applying this geothermometer to primary melts (not erupted lavas), one can estimate how hot the source mantle was when it was chemically in equilibrium with melt (in an averaged sense, because primary melt is an aggregate of polybaric melts).*

Observation 4: Isotope Geochemistry

The simplest way to lower the Mg# of the source mantle is to add subducted crust to pyrolitic mantle. Assuming that the source mantle is indeed such a composite of recycled crust and normal mantle, we can use isotope data to constrain the nature of the recycled crust. Pb, Nd, and Hf isotope data suggest that the original formation age of the recycled crust must be relatively young, in the range of 0.5-0.7 Ga [*Hanan & Graham*, 1996; *Korenaga & Kelemen*, 2000; *Lesher*, 2002] (Figure 8). Interestingly, this estimated age is consistent with the closure of the Iapetus (proto-Atlantic) Ocean. Based on this coincidence, *Korenaga & Kelemen* [2000] speculated that the North Atlantic igneous province might originate in the short-term recycling of the Iapetus MORB. This short-term recycling is most compatible with upper-mantle dynamics.

It has been suggested that Pangea experienced significant northward motion since the Caledonian orogeny and that this motion destroyed a direct link between subducted crust and the suture. It should be noted, however, that it is impossible to resolve the *relative* motion of a supercontinent with respect to the underlying mantle from paleomagnetic data because of the possibility of true polar wander. The geology of Pangea's leading edge suggests that true polar wander most likely occurred during the Permo-Triassic [*Marcano et al.*, 1999], in which case the entire mantle rotated as a whole and no significant shear is expected between Pangea and sublithospheric mantle. Thus, the northward migration of the supercontinent does not pose an impediment to short-term recycling.

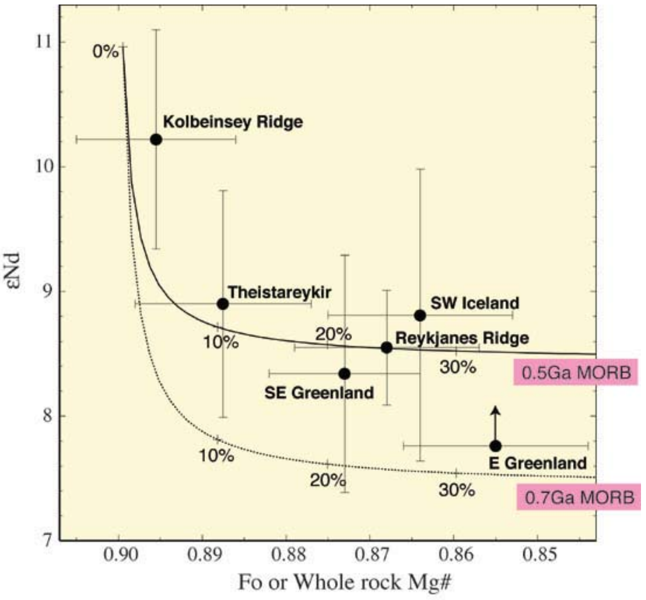
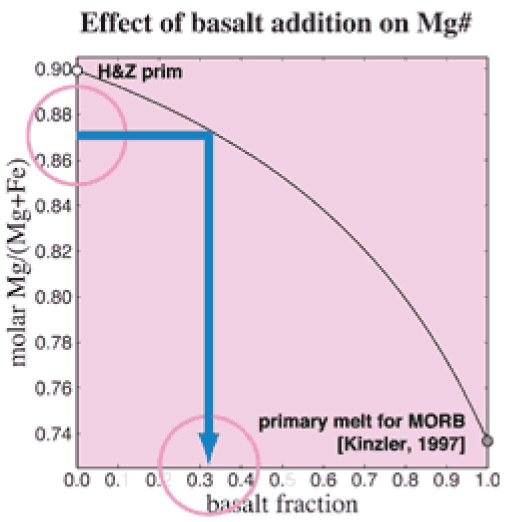


Figure 8. *Covariation of epsilon Nd and estimated whole rock Mg# for the six regions in the North Atlantic igneous province. To illustrate the effect of basalt addition, mixing curves between depleted pyrolite mantle and 0.5 Ga (solid) or 0.7 Ga (dotted), normal MORB are also shown. See Korenaga & Kelemen [2000] for details.*

Dynamical Dilemma

To lower the Mg# of the source mantle to as low as ~0.87, we need to add a very large amount of recycled oceanic crust (Figure 9); the volume fraction of the recycled crust should be as much as 20-30% of the source mantle. Whereas such fertile mantle can result in a very high-degree of melting without a notable thermal anomaly, it is much denser than normal pyrolite. Such fertile mantle requires an excess temperature anomaly of 200-300K to become just neutrally buoyant. How can such dense mantle rise in the first place, without a large thermal anomaly? Because fertile mantle has an intrinsic density excess, its potential contribution to excess magmatism has often been discounted at the outset - it appears to be simply physically implausible. Previous numerical studies on the dynamics of fertile mantle (e.g., eclogite-bearing plumes) [*Cordery et al.*, 1997; *Leitch & Davies*, 2001] have circumvented this density issue by neglecting it (!), which does not seem to be an attractive solution. As explained below, however, the upwelling of dense fertile mantle may be a natural consequence of multi-scale mantle dynamics.



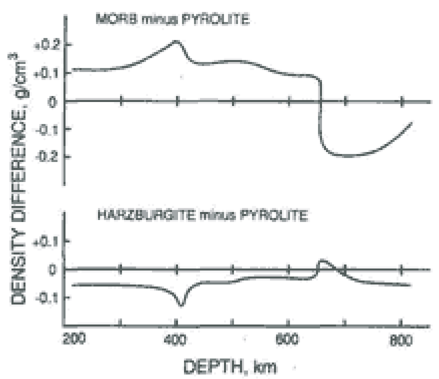


Fig. 3. Density profiles displayed by pyrolite, harzburgite and MORB compositions along the Brown and Shankland geotherm at depths down to 800 km.

Figure 9. (previous page) *Mg# of source mantle can be affected by addition of recycle oceanic crust. The influence of this addition on whole-rock Mg# is not linear, and to lower Mg# down to ~0.87, as 30% of recycled oceanic crust is required to be mixed with pyrolitic mantle.* ***(right)*** *Because basalt is transformed into eclogite at a depth of ~50-60 km, basalt addition to normal mantle results in an increase in bulk density (after Ringwood & Irifune [1988]). The density difference of 0.1 g/cm³ is equivalent to a temperature anomaly of 1000 K.*

Solution: Whole-mantle Sublithospheric Convection

Sublithospheric convection driven by surface cooling can naturally resolve the above dynamical dilemma, when considered in the whole-mantle framework. Sublithospheric convection, which is often called small-scale convection, has been traditionally studied in an upper-mantle framework. The base of the upper mantle (i.e., the 660-km discontinuity) is not necessarily an impermeable boundary. For a relatively short duration (*e.g.*, ~100 Myr), it can be considered as impermeable, but realistic viscous layering and the endothermic phase change expected at this depth is not strong enough to maintain the layered convection state forever. Such a layered state eventually breaks down, and when this happens, strong counter upwelling from the lower mantle is expected to compensate downwelling from the upper mantle. This mass-conserving flow, which takes place together with buoyancy-driven flow, could be strong enough to entrain dense fertile mantle and bring it to the surface.

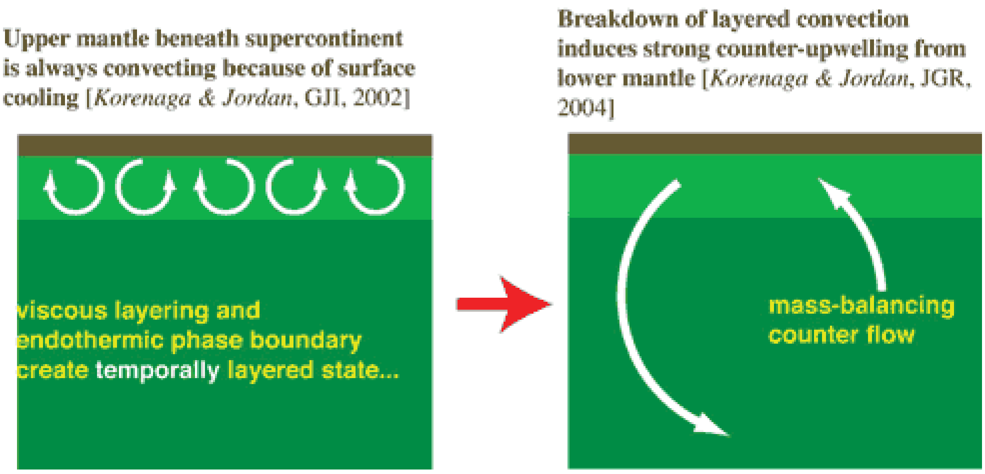


Figure 10. *Concept of whole-mantle-scale sublithospheric convection and mass-conserving counter upwelling. This rich multi-scale dynamics of sublithospheric convection was not recognized until very recently.*

New Working Hypothesis

Voluminous breakup magmatism may simply reflect compositional heterogeneity in the upper mantle, not excess mantle temperature associated with a deep thermal boundary layer. With the above counter-upwelling mechanism, we are now ready to build a new working hypothesis for the origin of the North Atlantic igneous province as well as the Iceland hotspot. To make a hypothesis that can satisfy all the major observational constraints is difficult. So far I have been able to come up with only one dynamically-consistent scenario, which is shown below. I am not aware of any alternative hypotheses that have a similar capability.

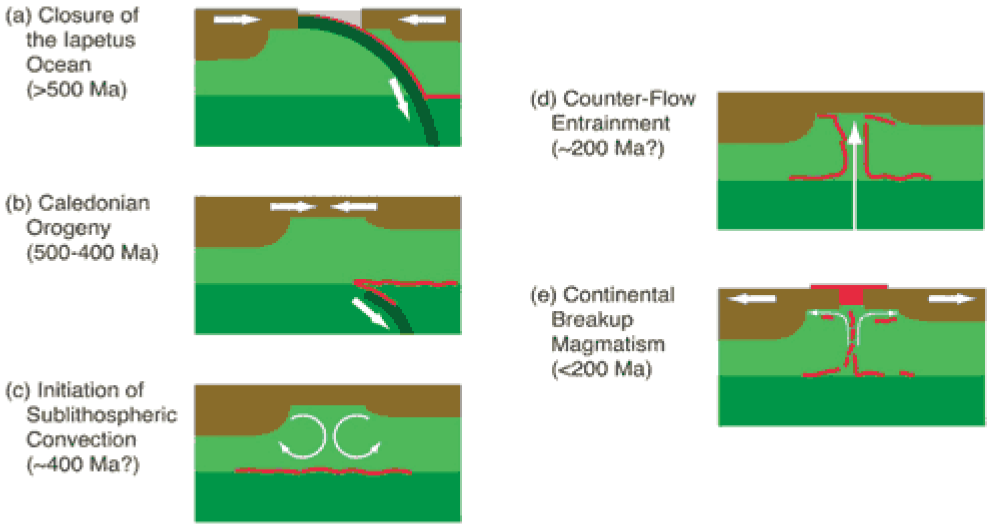


Figure 11. *Schematic illustration of a possible scenario for the formation of a large igneous province during the breakup of Pangea. (a) The closure of the Iapetus Ocean took place prior to ~500 Ma, and during this period, a layer of oceanic crust was segregated from the subducting slab at the base of the mantle transition zone. (b) The Iapetus Ocean diminished, and the Caledonian Orogeny took place during ~500-400 Ma. (c) The supercontinent Pangea was assembled during ~320-170 Ma, and sublithospheric convection was initiated beneath suture zones. Though convective motion is depicted here two-dimensionally, it is most likely three-dimensional, with strong convection confined in the out-of-plane direction. (d) Sublithospheric convection was confined in the upper mantle for a while, but eventually this layering broke down, and mass-conserving counter upwelling entrained crustal components to the base of lithosphere. (e) Plate-driven flow during continental rifting (e.g., ~60 Ma for the North Atlantic) further assisted this entrainment process, and the circulation of fertile mantle to shallow depths resulted in a high degree of melting, which is observed as flood basalt volcanism.*

The crustal component of a subducting slab has a higher viscosity than the lithospheric component and ambient mantle because of its higher garnet content, and it also becomes strongly buoyant below the 660-km discontinuity. Segregation of oceanic crust at the base of the mantle transition zone is debatable, but at least it is physically plausible if these viscosity and density contrasts are taken into account [*e.g.*, *Karato*, 1997]. This segregation stage (Figure 11a,b) is essential for creating fertile mantle. If subducted crust and depleted lithosphere is simply remixed the original pyrolite mantle only is recovered, which is not anomalously fertile.

The initiation of sublithospheric convection (Figure 11c) is a natural consequence of surface cooling, which takes place continually everywhere on Earth. This convection mechanism is fundamentally different from so-called “edge-driven” convection, which requires a special (and probably unrealistic) setup of lithospheric structure and asthenospheric condition (see *Korenaga & Jordan* [2001, 2002] for detailed discussion. Editor’s note: see also EDGE page).

Mass-conserving counter flow and any entrainment of oceanic crust (Figure 11d) does not necessarily take place beneath the suture zone as depicted in the cartoon. Counter flow could take place somewhere else; if it happens beneath a thick continental craton, it would not be manifest in the surface geology. Also, even if counter flow does occur beneath a suture zone, entrainment would not take place without crustal fragments floating at 660 km. This may explain the limited occurrence (both spatially and temporally) of flood basalt provinces during the opening of the Atlantic.

Once raised to shallow depths (Figure 11e), crustal components start to melt much earlier than surrounding mantle. The liquidus of the crustal component is lower than the solidus of the surrounding pyrolite; adiabatically upwelling mantle with a potential temperature of 1623 K, for example, intersects the solidus and liquidus of anhydrous mid-ocean ridge basalt at ~150 km and ~70 km, respectively [*e.g.*, *Yasuda et al*., 1994]. This preferential melting of crustal fragments results in strong melt-retention buoyancy, which can further enhance upwelling.

Counter-flow entrainment can bring up fertile mantle to very shallow depths. This is important, because it can explain the formation of a flood basalt province as soon as continents are rifted apart. If plate-driven flow is the only mechanism that drags up dense crustal fragments, temporal coincidence between rifting and anomalous magmatism cannot be explained.

Numerical Modeling of Counter-Flow Entrainment

To test the feasibility of this new working hypothesis, especially the counter-flow entrainment scenario, some preliminary numerical modeling has been done. Interested readers are referred to *Korenaga* [2004] for a complete description. Here I just explain the main results and their geological implications. Two models are shown for comparison: one with isochemical mantle and the other with segregated crustal fragments. The former serves as a reference, showing what would be expected for the simplest setting.

Color indicates potential temperature, yellow is hottest, and dark blue coldest. The model extends down to the base of the whole mantle. The lower mantle has 30 times higher viscosity than the upper mantle, and there is also a moderate endothermic phase change at 660 km. These numerical models are designed to investigate the dynamic state of the mantle prior to continental breakup.

Case A: Isochemical Model

Viscosity layering and the endothermic phase change result in layered convection at least partially and also temporally. A completely layered state is dynamically unstable, and whole-mantle-scale flow periodically flushes through the system. This is very similar in nature to what is known as “mantle avalanche” in mantle convection models, though the temperature variations involved are much smaller here. Whenever large-scale downwelling takes place, there is also corresponding upwelling with similar strength. (Note that whole-mantle-scale flow is much faster than upper-mantle-scale flow).

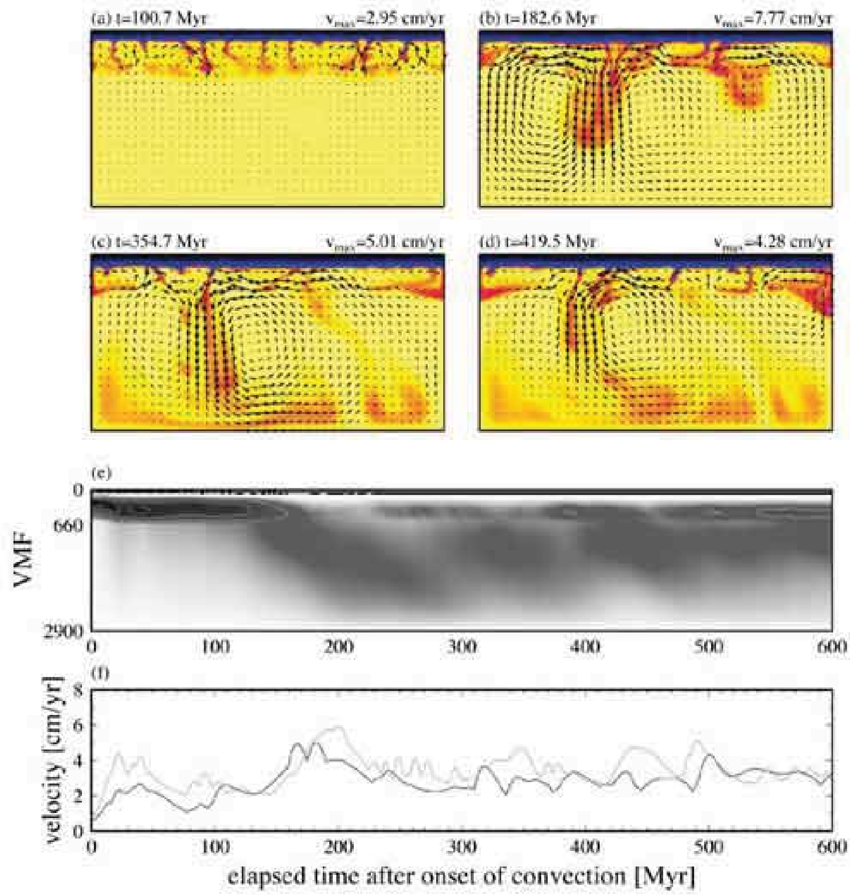


Figure 12: Case A. (a-d) Snapshots of temperature and velocity fields. Velocity arrows are normalized to maximum velocity, which is denoted at every snapshot. Elapsed time shown here is measured from the onset of convection, after which lithosphere is thicker than ~100 km. (e) Vertical mass flux (VMF) diagnostic with contour interval of 2.0. It can be seen that most of the vertical mass flux is confined above 660 km for the first 150 Myr. (f) Maximum upwelling (solid) and downwelling (dotted) velocities observed in the model domain.

Case B: With Segregated Crust (green dots)

Case B includes segregated crustal fragments floating at 660 km (shown as green dots). These crustal fragments are denser than the upper mantle, but more buoyant than the lower mantle. Therefore, it is very difficult to push them down, and downwelling takes place preferentially away from these fragments. This results in the fragments spreading out horizontally, which makes them more easily penetrated by counter upwelling. Counter upwelling is indeed strong enough to entrain as much as 20-30% of the fragments (see bottom of the figure). Interestingly, upwelling is also spatially focused; it is not broad and diffuse.

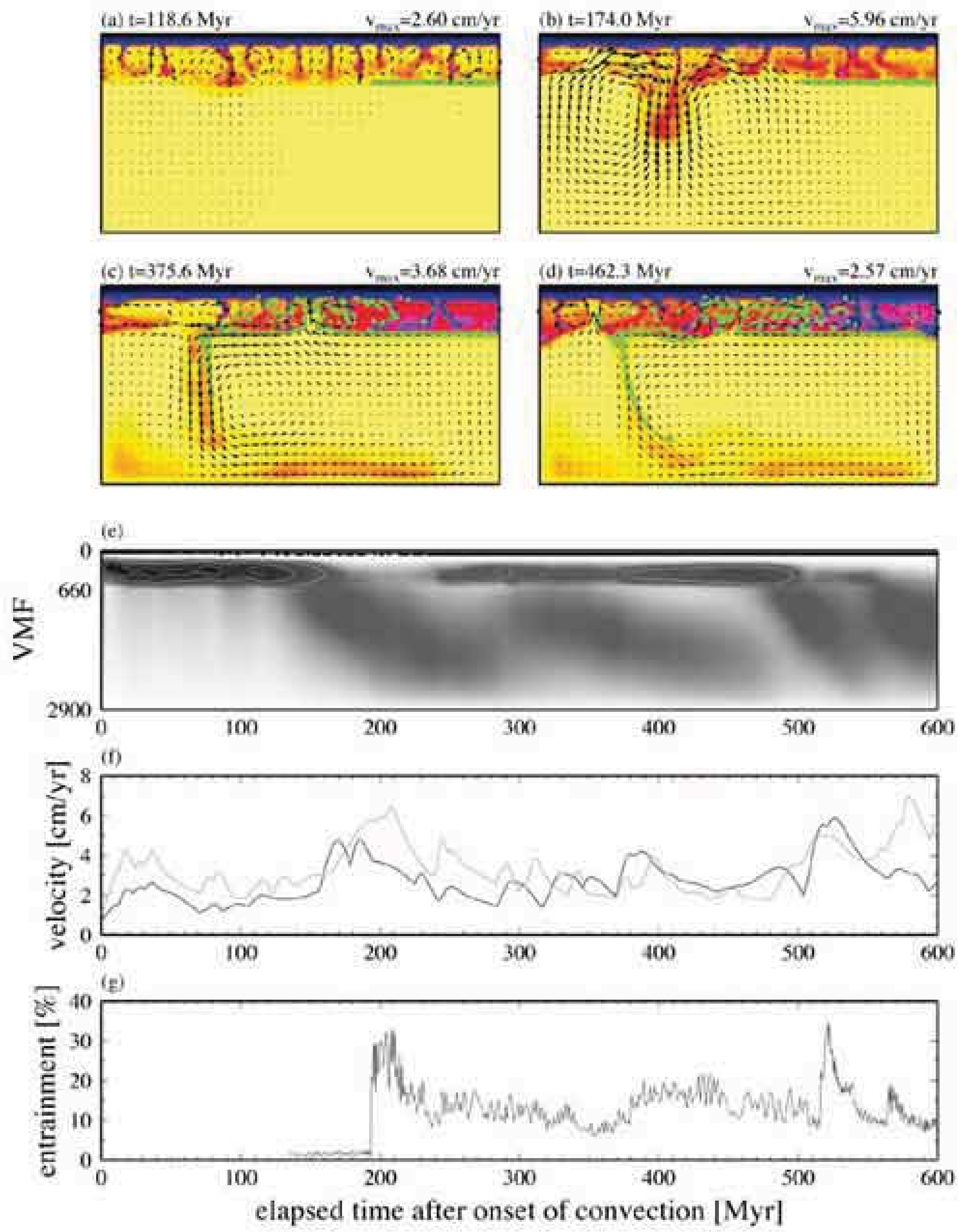


Figure 13: Case B. (a-d) Snapshots of temperature and velocity fields, as in the previous figure. Tracers for crustal fragments are denoted by green circles. (e) Vertical mass flux diagnostic. (f) Maximum upwelling (solid) and downwelling velocities (dotted). (g) Maximum fraction of crustal fragments entrained into the upper mantle shallower than 410 km.

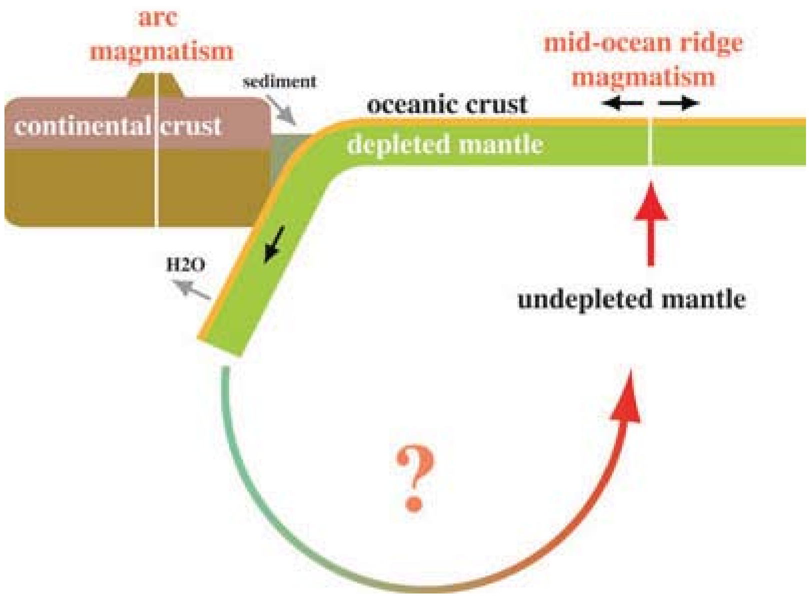
Concluding Remarks

My convection model is relatively simple, i.e., a cooling whole-mantle system with segregated crust accumulated at the 660-km discontinuity. Yet, this incomplete state of mantle mixing can induce quite complex dynamics, with profound implications for the origin of anomalous magmatism. Voluminous breakup magmatism may simply reflect compositional heterogeneity in the upper mantle, not excess mantle temperature associated with a deep thermal boundary layer. It is less problematic, for example, to account for the proximity of the Iceland and the Jan Mayen hotspots, which are only ~800 km apart, by upper mantle heterogeneity than two closely-located plumes rising from the depth of ~3000 km. The mobility of the Iceland hotspot with respect to other Indo-Atlantic hotspots [*Norton*, 2000] is also no more surprising because counter-flow entrainment is not strongly anchored in the mantle. In addition, the amount of crustal fragments embedded in the mantle matrix is unlikely to be constant over time, considering the random nature of entrainment, so it is natural to expect time-varying melt productivity, which we may observe today as the V-shaped Reykjanes Ridge [*Vogt*, 1971].

Though my model may be best characterized by the chemically heterogeneous upper mantle, it is not strictly an upper-mantle model. The lower mantle is also involved; counter upwelling is supplied from the lower mantle. This may explain why the Iceland hotspot has high $^3He/^4He$ ratios, which are usually considered as a signature of relatively undegassed deep mantle reservoir [e.g., *Kurz et al.*, 1982] (Editor's note: see also Helium fundamentals page, however, for an upper-mantle model for high-$^3He/^4He$), whereas mantle tomography exhibits low velocity anomalies only in the upper mantle. Sublithospheric mantle is likely to be in a fully dynamic state on various spatial scales, which is clearly seen even in the isochemical case. Rifting above downwelling mantle may give rise to non-volcanic rifted margins such as the Newfoundland Basin and the Iberia margin.

Because entrained crustal fragments start to melt deeper than surrounding mantle, melt-retention buoyancy becomes important. This contrasts with the melting of homogeneous mantle beneath normal mid-ocean ridges, for which retention buoyancy is probably small owing to the formation of a porous melt network. Thus, a recent seismic study suggests buoyancy-driven mantle upwelling beneath Iceland [*Gaherty*, 2001] is consistent with the melting of chemically heterogeneous mantle. Rapid lateral spreading in response to the basal topography of lithosphere is also possible for upwelling mantle with high melt-retention buoyancy; such dynamics are not limited to plume-lithosphere interaction [*Sleep*, 1997]. Eventually, the surrounding mantle matrix starts to melt at shallow depths (~60 km), and melt from the entrained crust will escape into the porous network developed in the matrix.

The thermal plume hypothesis assumes that the mantle is homogeneous in terms of major-element composition and attributes excess magmatism to elevated mantle temperature only. This assumption is startling in the light of the well-accepted fact that trace-element and isotope heterogeneities exist in the mantle. Even if a perfectly homogeneous mantle existed at some point, it is not obvious how such homogeneity could be maintained because plate tectonics continuously introduces heterogeneity by chemical differentiation at mid-ocean ridges. Remixing could well be incomplete sometime somewhere in a complex convection system. Beyond the North Atlantic igneous province, the number data available to distinguish between the thermal and chemical origins is surprisingly small. Speculation is fine and can be thought-provoking, but we really need to acquire more new data to move on, along with developing a more thorough understanding of mantle dynamics.



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