Edge Driven Convection and Iceland

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One of the alternative hypotheses for hotspot volcanism is Edge-Driven Convection (EDC). A small-scale convective instability forms at any step or discontinuous change in thickness in a thermal boundary layer [e.g., Elder, 1976]. The EDC hypothesis envisions that this instability will form at boundaries between stable cratons and oceanic, or young continental, lithosphere [e.g., King and Anderson, 1995; 1998]. Because this is a relatively weak instability, large lateral variations in temperature or fast plate-scale flow can overwhelm EDC instabilities. (These same factors would also overwhelm most plume instabilities.) In the Central Atlantic, seismic tomography supports the EDC hypothesis–seismically fast anomalies (presumably cold downwellings) are observed at the edge of the South American and West African cratons (Figure 1) just where we would expect the downwelling limbs of EDC to be located. King and Ritsema [2000] conclude that many, if not all, of the off-ridge Central and South Atlantic hotspots could be explained by EDC.

The question remains, “Can an EDC mechanism explain the excess volcanism at Iceland (and the Azores)?” The answer is not as clear as we would like, yet it is premature to throw out the EDC hypothesis. The biggest obstacle to considering the EDC hypothesis for Iceland is that there are no seismically fast anomalies beneath the Greenland and Scandinavian cratons. In order to properly evaluate whether this is strong enough to rule out EDC, we need to understand the time evolution and the effect of the width of the ocean basin on the planform of EDC. We know that the North Atlantic began opening later than the Central and South Atlantic. Based on the temporal evolution of the EDC instability, it is possible that a downwelling broad enough to be observed seismic tomography may not yet have formed. The North Atlantic is the narrowest part of the Atlantic basin. A detailed parameter study reveals that an EDC instability at one or both of the cratons bounding the North Atlantic could up well at the Mid-Atlantic ridge.

In the central and southern Atlantic, which are much wider than the North Atlantic, hotspots occur off the ridge axis. This is in agreement with the study of basin width and EDC. Furthermore, EDC predicts that these upwellings should be weaker because, the of the time since the beginning of spreading in the southern and central parts of the Atlantic and, only one EDC instability contributes to each of these hotspots whereas EDC instabilities from both sides contribute to ridge-centered hotspots.

To understand the origin of Iceland (and the Azores), it is important to explain not only the excess volcanism on the Mid-Atlantic ridge, but also to understand the North Atlantic geoid and topographic anomalies. The spherical harmonic degree 3-12 expansion of the geoid from the GEM-T2 model is contoured in Figure 2. I have purposely removed the degree 2 term of the expansion because the large $l = 2, m = 0$ term obscures the lateral variation in the geoid. There is a broad geoid high in the North Atlantic extending from north of Iceland, along the Mid-Atlantic ridge, to south of the Azores. For reference, the star at the southern tip of the white oval represents the Azores and the one at the northern tip of the white oval represents the Jan Mayen hotspot. The star just to the south of Jan Mayen represents the Iceland hotspot.

The North Atlantic geoid high one of several prominent geoid highs on the planet. Others include the geoid high in the western Pacific associated with the Solomon and New Britain subduction zones [c.f., Hager, 1984] and the geoid high in the southern Indian Ocean, associated with the uplifted plateau of southern Africa [Lithgow-Bertelloni and Silver, 1998; Gurnis *et al.*, 2000]. The previously cited studies propose that the African/Indian geoid high and the elevated

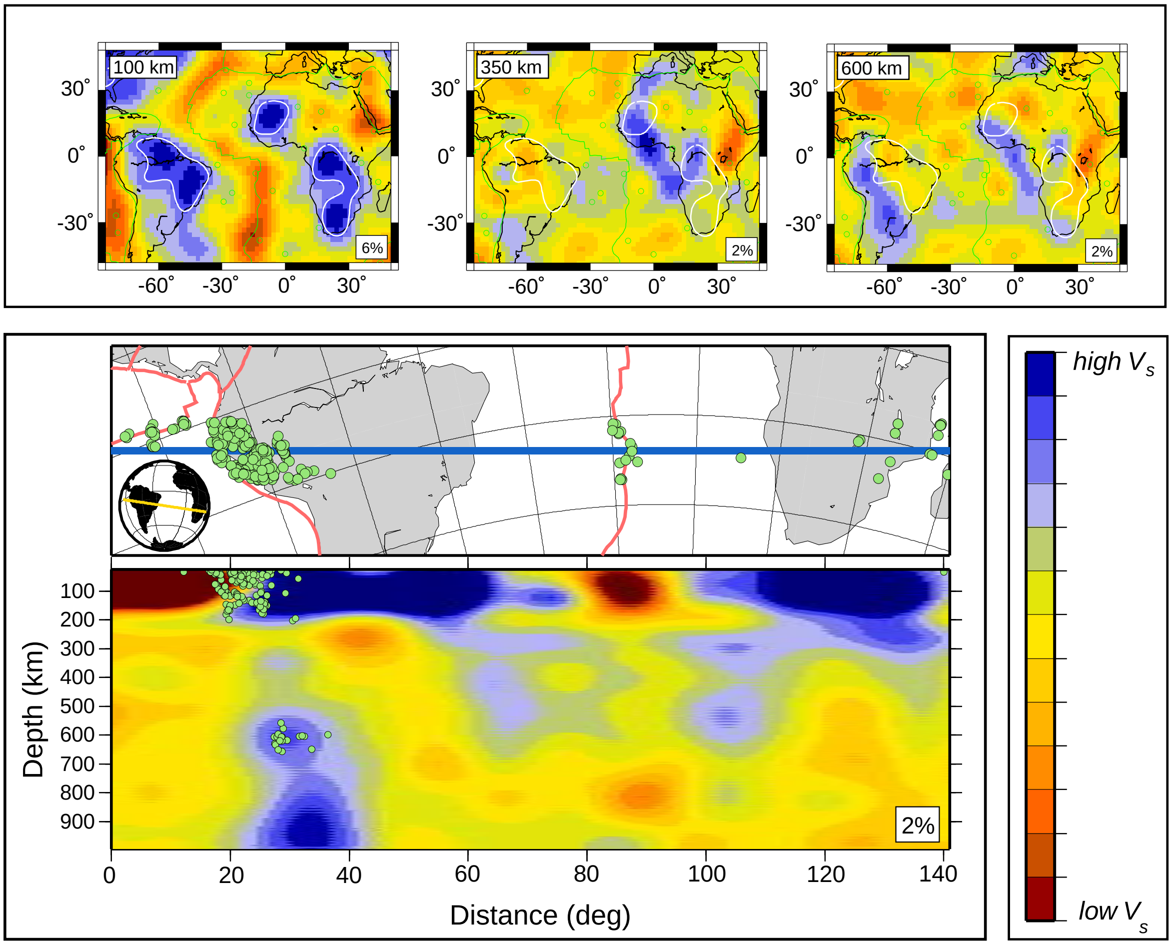

Figure 1: (A) Horizontal cross-sections through seismic tomography model S20RTS [Ritsema *et al.*, 1999] at at depths of 100 km, 350 km, and 600 km. Relatively high velocity and low velocity regions are indicated by blue and red colors, respectively, with an intensity that is proportional to the amplitude of the velocity perturbation from the PREM. Green lines represent plate boundaries. White lines circumvent regions in the mantle where the seismic velocity at a depth of 100 km is larger than in the PREM by 4% or more. These regions roughly outline the location of Precambrian cratons. (B) A 140 deg wide cross–section through S20RTS across South America and southern Africa. The green circles indicates locations of earthquakes in the Harvard CMT catalog.

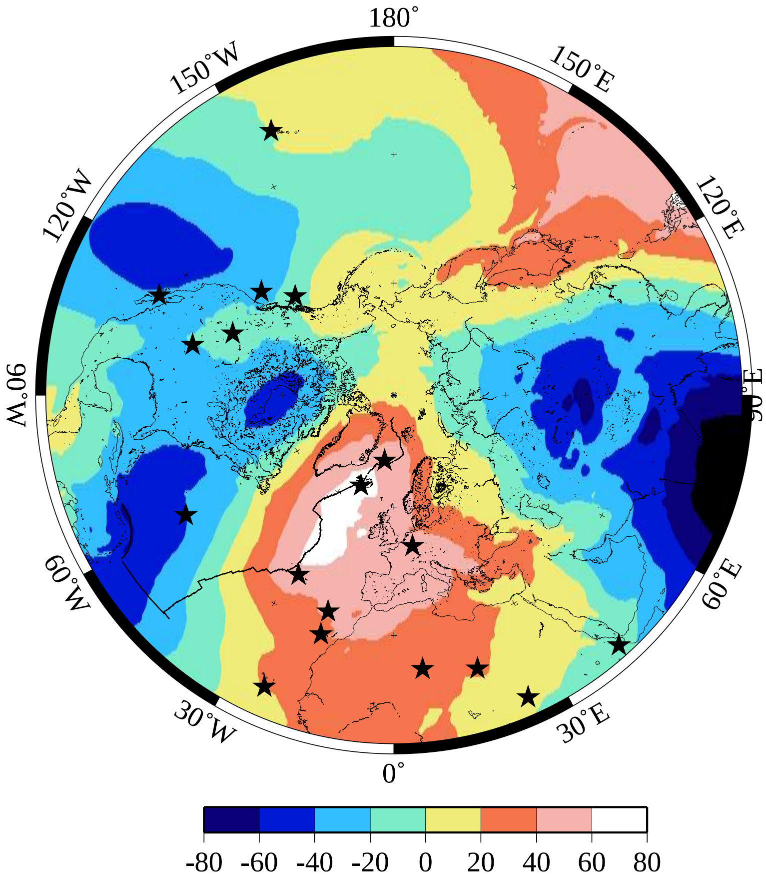

Figure 2: The North Atlantic geoid from GEM-T2. The boundary between the North American and European Plate is shown by the black line. The solid stars are the locations of hotspots.

plateaus in southern Africa are caused by mantle flow driven by a large, slow seismic velocity anomaly in the deep mantle, sometimes referred to as 'the Great African plume.' In hotspot swell studies, features this wavelength are removed by filtering. Interestingly, Iceland is one of three significant geoid anomalies that remain unexplained after accounting for subducted slabs and glacial isostatic adjustment [Simons *et al.*, 1997; Mark Simons thesis].

Seeking a consistent explanation for the southern Indian/African and the North Atlantic geoid highs, it is clearly tempting to relate the North Atlantic geoid high to a deep sourced mantle upwelling beneath Iceland. Note that the scale and morphology of 'the Great African plume', and presumably the deep upwelling that supports the North Atlantic geoid and topographic anomalies is completely different than what is envisioned in the plume hypothesis. Within the field of Figure 2 there are many other hotspots including: Bermuda, Azores, Canary Islands, Cape Verde, Madeira and Yellowstone (solid starts in Figure 2). There are no comparable features in the geoid that can be associated with these hotspots (except for the anomaly along the Mid-Atlantic Ridge which encompasses both Iceland and the Azores). Geoid anomalies associated hotspots are typically on the order of 1-5 meters [Crough, 1983, Monnereau and Cazenave, 1990; Sleep, 1990] whereas the North Atlantic geoid anomaly is on the order of 50 meters. This would argue that either there is more than one mechanism for hotspot volcanism or that there is no direct relation between the North Atlantic geoid and topographic anomalies and the excess volcanism at Iceland.

Most of the gravity and topography swells associated with the Hawaiian hotspot can be explained by compositional, as opposed to thermal, density anomalies [McNutt *et al.*, 1998]. Further, the heatflow anomaly at Hawaii is better explained by a hydrothermal circulation model than it is by residual heat from a mantle plume [Harris *et al.*, 2000]. After accounting for hydrothermal circulation and compositional density effects, the remaining anomalies that could represent the thermal plume are very small. Hawaii and Iceland are often considered the type examples of plumes. If the swell and geoid at Iceland are the results of a deep mantle plume, then it is truly a plume with no equal on the planet.

One can envision several experiments to distinguish between a deep and shallow source for the North Atlantic surface anomalies. Most obviously, the magnitude geoid and topographic anomalies generated by EDC can be compared with the North Atlantic anomalies. It is difficult to produce the magnitude of geoid and topographic anomalies with EDC calculations; however, work is still underway. Geoid and topographic swells from temperature-dependent plume calculations are with realistic parameterizations are compared with observations. Most of the surface anomalies from these calculations are the related to upper mantle plume/lithosphere thermal anomalies as opposed to deep anomalies. From this we conclude that it may not be possible to completely resolve upper versus lower mantle sources for surface anomalies. (In the sense that the upper mantle source in this case, the plume influenced lithosphere 'lithospheric erosion,' is related to the deep mantle instability.) However, the spatial extent of the Great African plume, which is thought to be responsible for similar-scale geoid and topographic anomalies in the southern Indian ocean, is quite different from the plume structures envisioned in the plume hypothesis. By comparing at the pattern of seismic tomography in the upper and lower mantle with the pattern of the residual geoid from Simons global geoid analysis, we can attempt to isolate the source of the anomalies by matching spatial patterns. A preliminary investigation is promising and more results will be presented.

My working hypothesis is that the volcanism has an upper mantle (EDC) origin while the topography and geoid has a deep mantle origin (like the proposed South African/Southern Indian ocean geoid and topographic anomalies).

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