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Is Iceland underlain by a plume in the lower mantle? Seismology and helium isotopes

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SUMMARY

Tomographic images reveal an apparent fundamental disagreement in the interpretations of seismic data pertaining to the depth of the source of lavas erupted in the Iceland region and the assumptions in helium geochemistry modelling. Four recent independent tomography experiments image a major, strong, low-wave-speed anomaly in the upper mantle beneath Iceland that does not continue down into the lower mantle, confirming earlier studies. On the other hand, some $^3He/^4He$ ratios measured in volcanic rocks from the Iceland region are amongst the highest on Earth. Elevated $^3He/^4He$ ratios are conventionally viewed as resulting from excess ^3He from a little-degassed, primitive reservoir, often assumed to be in the lower mantle, and a high $^3He/^4He$ ratio is regarded as the most powerful geochemical indicator of a lower mantle plume. Suggested explanations for this disagreement include a model whereby material is transported up from the lower mantle by a structure that is too small to be detected by seismic tomography, and a model whereby high $^3He/^4He$ ratios arise from the upper mantle. These results have significant implications for models of plumes elsewhere.

Key words: geochemistry, helium isotopes, plumes, seismology, tomography.

1 SEISMIC TOMOGRAPHY IMAGES OF THE MANTLE BENEATH ICELAND

Early tomographic studies found the Iceland region to be underlain by a low-wave-speed anomaly confined to the upper mantle (Hager & Clayton 1989; Zhou 1996). Three recent whole-mantle tomography experiments provide improved images of the mantle beneath Iceland (Bijwaard & Spakman 1999; Ritsema *et al*. 1999; Megnin & Romanowicz 2000). Ritsema *et al*. (1999) determined an *S*-wave-speed model using over 2 000 000 data including surface wave phase velocities, body wave traveltimes and free-oscillation splitting measurements from digital global and regional networks. Resolution of the structure beneath the north Atlantic is ~1000 km laterally and ~150 km vertically in the transition zone. An *S*-wave-speed anomaly that is up to 2.5 per cent slow compared with the Preliminary Reference Earth Model (PREM, Dziewonski & Anderson 1981) is imaged that fills much of the north Atlantic between Greenland and Scandinavia. Possible explanations of such anomalously low wave speeds in the mantle are high temperature, perhaps accompanied by partial melt, or a buoyant upwelling associated with the opening of the north Atlantic.

In the tomographic image, the strong, low-wave-speed anomaly stops abruptly at the base of the upper mantle at ~650 km depth. Immediately beneath, the *S*-wave speed is slightly higher than the average for that depth. Low-wave-speed anomalies of up to ~0.5 per cent are again encountered at ~1000 km depth, but a direct, vertical connection with the strong, upper mantle low-wave-speed anomaly is not observed. Similar weak anomalies are imaged elsewhere in the lower mantle where they are unrelated to hotspots.

A similar result is obtained by global V_{SH} waveform tomography. Megnin & Romanowicz (2000) inverted hand-picked, time-domain waveforms of Love waves, body waves and first- and second-orbit higher-mode arrivals. Resolution in their model is ~900 km horizontally and 100 km vertically (C. Megnin, personal communication, 2000). A broad, strong, low-wave-speed anomaly is again imaged, in this case confined to the top ~300 km of the upper mantle. Immediately beneath the 650 km discontinuity, wave speeds are slightly high, and below that, in the mid-lower mantle, up to a few tenths of a per cent low.

A whole-mantle, *P*-wave-speed tomography study by Bijwaard & Spakman (1999) used a reprocessed set of global arrival time data from the International Seismological Centre (Engdahl *et al.*

1998). Those authors present a cross-section passing through Iceland that shows a continuous, low-wave-speed body extending from the surface to the core–mantle boundary. However, the apparent first-order inconsistency between this particular cross-section and the models of Ritsema *et al.* (1999) and Megnin & Romanowicz (2000) is a result of the colour scale used. Bijwaard & Spakman (1999) also found much stronger low-wave-speed anomalies in the upper mantle (>5 per cent) than in the lower mantle ($<\sim 0.5$ per cent), and had to saturate the colour scale they used at <10 per cent of the maximum anomaly in order to illustrate an apparently continuous low-wave-speed structure extending throughout the mantle. Also, the apparent connection of the upper mantle body to the lower mantle body does not lie beneath Iceland but ~ 300 km to the southeast, beneath the Iceland–Faroe ridge. The narrow lateral extent of the section presented furthermore conceals the fact that similar low-wave-speed anomalies extending throughout much of the mantle also underlie the neighbouring Canadian craton and Scandinavia, where plumes are not expected. In fact, the results of Ritsema *et al.* (1999), Megnin & Romanowicz (2000) and Bijwaard & Spakman (1999) are, to first-order, in agreement and also in agreement with the early studies of Clayton & Hager (1989) and Zhou (1996).

A recent teleseismic tomography experiment conducted in Iceland detected a low-wave-speed body whose variation in morphology with depth suggests it does not extend deeper than the mantle transition zone (Foulger *et al.* 2000, 2001). The experiment involved a dense, uniform, broad-band seismometer network that was deployed in Iceland for two years, and utilized several times more data than previous teleseismic tomography experiments there (Tryggvason *et al.* 1983; Wolfe *et al.* 1997; Keller *et al.* 2000). An extensive, relatively low-wave-speed body approximately 200 km in diameter was detected beneath Iceland. The anomaly is cylindrical in the upper 250 km, but tabular beneath this, down to the limit of good resolution at ~ 400 km. The tabular body underlies, and is parallel to, the spreading plate boundary. Such a morphological transition is not expected partway down a plume that is continuous throughout the mantle, but it is expected towards the bottom of buoyant upwellings that may be triggered by a variety of processes including partial basal heating, plate separation and local convection (Houseman 1990; Parmentier & Morgan 1990; Anderson 1998a). EDGE convection, for example (King & Anderson 1995, 1998), is driven from above and by lateral temperature gradients, and induces small-scale convection that terminates abruptly at the 650 km phase boundary (King & Ritsema 2000). Although the teleseismic tomography could not resolve structure deeper than 400 km, the morphology of the seismic anomaly nevertheless suggests that its bottom is approached at a depth of about 400 km.

The width of the upper mantle anomaly beneath the Iceland region is poorly constrained by the tomography experiments that have been carried out to date. Whole-mantle tomography provides an amplitude-attenuated, spatially smeared image of relatively small anomalies because of coarse parametrization of the Earth. Thus, the $\sim 1{,}000$ km wide, low-wave-speed anomaly imaged to extend for almost the full width of the north Atlantic at the latitude of Iceland could result from a stronger, more localized anomaly. Teleseismic tomography images relative wave speeds only. It shows that the anomaly is strong beneath the centre of Iceland relative to peripheral areas, but it is not able to reveal its absolute extent. The integrated anomaly imaged by whole-mantle tomography is roughly twice as large as the 200 km diameter anomaly observed by teleseismic tomography, which suggests that the latter may be detecting the strong core of an anomaly that may be broader than Iceland itself.

Most importantly, all the tomographic studies agree that there is a first-order discontinuity in structure between the upper and lower mantles beneath Iceland. This suggests that the strong, low-wave-speed anomaly beneath Iceland is confined to the upper mantle. Other, indirect seismic evidence has been presented in support of a deeper structure beneath the Iceland region, including evidence for partial melt at the core–mantle boundary (Helmberger *et al.* 1998) and thinning of the transition zone (Shen *et al.* 1998). The transition zone beneath Iceland is, however, no thinner than it is beneath areas where no plume is expected, e.g. southern California (Gurrola & Minster 1998), and local thinning may be caused by a variety of reasons including phase transformations, chemical layering, variations in mantle hydration, kinetic effects and normal variations in mantle temperature (Anderson 1989, 2000b; Solomatov & Stevenson 1994; Wood 1995). Weak low-wave-speed anomalies are imaged beneath the Iceland region in the lower mantle but they are not vertically continuous beneath Iceland or they are not connected with the upper mantle body, and the repeatability between studies of their shapes and extents is poor. These results are inconsistent with a model of a vertical, dynamically continuous, plume-like body traversing the whole mantle beneath Iceland.

2 HELIUM ISOTOPES AND THE ICELAND HOTSPOT

The tomography results are seemingly at odds with the conventional geochemical assumption of the origin of noble gas isotopic signatures, in particular that of helium (e.g. Hanan & Graham 1996; Farley & Neroda 1998). Lavas that have $^3He/^4He$ ratios greater than 'typical' N-MORB have been interpreted as containing an excess of a primitive, high-^3He, little-degassed component that is widely held to come from a source deeper than the upper mantle (Kurz *et al.* 1983b; Rison & Craig 1983b). The 'typical' N-MORB $^3He/^4He$ ratio is usually considered to be $\sim 8 \pm 1$ Ra (Fisher 1986), where Ra is the atmospheric $^3He/^4He$ ratio of 1.38×10^{-6}. This value is obtained by filtering out data thought to have been influenced by plumes. An unfiltered $^3He/^4He$ ratio for the global spreading ridge is 9.1 ± 3.6 (Anderson 2000c), although this high estimate is, to some extent, influenced by disproportionate reporting of high values from areas considered to be interesting. Despite the larger standard deviation of the unfiltered estimate, rocks with unusually high $^3He/^4He$ ratios, commonly exceeding 20 Ra, are widespread at some hotspots.

Recent helium isotope studies of lavas erupted in the north Atlantic volcanic province over the last 60 Myr have revealed great variability in $^3He/^4He$ ratios in picrites, ranging from values much less than 8 Ra to very high values (Graham *et al.* 1998), with one late Tertiary picrite from Selardalur, Iceland, yielding one of the highest $^3He/^4He$ ratios ever measured for a terrestrial rock—37.7 ± 2 Ra ([He]$=0.89 \times 10^{-9}$ cc STP g^{-1}, or $\sim 10^{-3}$ of MORB) (Hilton *et al.* 1999). The helium isotopic signature of the ancestral and present Iceland hotspot is very comparable to that of Loihi, Hawaii, where a deep source has been advocated to explain the highest $^3He/^4He$ ratios there (Kurz *et al.* 1983a; Rison & Craig 1983a). Furthermore, the

Selardalur, Iceland sample with the most extreme $^3He/^4He$ value has Sr–Nd–Pb isotopic compositions (Hilton *et al.* 1999) that approximate closely the common mantle end-member ('C' or FOZO; Hart *et al.* 1992; Hanan & Graham 1996) that is assumed to reside in the lower mantle because it is a common component. From an isotopic perspective, the composition of some of the Iceland lavas would be normally interpreted as originating from a deep, primitive, little-degassed reservoir such as the lower mantle or the core–mantle boundary, although many of these lavas display little other geochemical evidence for such a component (Kempton *et al.* 2000).

3 DISCUSSION

The discrepancy between the interpretations of the tomography and the assumptions regarding the origin of the highest $^3He/^4He$ ratios in Icelandic rocks is one of the clearest manifestations of a growing inability to reconcile a mantle structure based on the assumption that a deep, primitive, high-^3He, little degassed reservoir is required by noble gas geochemistry with observed and modelled mantle structure and dynamics (e.g. Albarede 1998; Albarede & van der Hilst 1999; Davies 1999; Kellogg *et al.* 1999; van Keken & Ballentine 2001). Suggested explanations for this discrepancy include both models that involve mass flux from the lower mantle and models that do not.

It has been suggested that the highest $^3He/^4He$ ratios might arise from the diffusion of ^3He across the 650 km discontinuity from the lower mantle, without significant advection of other material, a process that would be invisible to tomography. This is unlikely because of the very low diffusion rates of helium in the Earth (Hart 1984). Alternatively, material might be transported up from the lower mantle through a conduit that is too narrow to be detected by seismology. A conduit $\leq \sim 100$ km wide would be undetectable, even if strong, and it is particularly difficult to image low-wave-speed bodies because waves diffracted around them may arrive before waves passing directly through. Such a structure would, however, have to cross the phase transition at 650 km depth without stalling, since that would cause it to spread out below that boundary, forming a low-wave-speed head. Such a head has not been observed, indicating that if a plume does rise from the lower mantle beneath Iceland, the Clapeyron slope of the phase transition at 650 km must be no steeper than about -2 MPa K^{-1}. A very narrow, hot conduit would also be transient, since thermal conduction would cause it to widen with time. Also, since the width of plumes is expected to be related to the viscosity of the surrounding mantle, it would be expected that a plume would be wider in the lower mantle than in the upper mantle, not narrower.

Recent geochemical studies based on trace elements (Fitton *et al.* 1997) and isotopes including helium (Kempton *et al.* 2000; Stuart *et al.* 2000) have suggested models where most of the mass flux of the Iceland hotspot originates in the upper mantle, with a relatively minor contribution from the lower mantle. Fitton *et al.* (1997) have suggested that lower mantle material may be drawn up in the core of a plume originating at the 650 km discontinuity. This might account for the highest $^3He/^4He$ signature observed. However, the narrow-conduit hypothesis suffers from the disadvantage that, if sufficiently small structures are proposed, it is essentially impossible to devise independent tests. Although such an argument does not rule out a narrow, lower mantle plume, untestable hypotheses are of no utility in science and should not be adopted in preference to other competing hypotheses.

If interpretations of the geochemical anomalies involving a substantial mass flux into the Iceland hotspot from the lower mantle are correct, an explanation is required for why this is apparently not seen seismically by whole-mantle tomography, and why the morphology of the upper mantle body imaged by teleseismic tomography suggests a shallow depth extent. The strong seismic anomalies in the upper mantle beneath central Iceland may be explained by temperatures elevated by ~ 200 K relative to peripheral areas. For a given temperature anomaly, seismic wave-speed anomalies in the deep lower mantle would be much less than in the upper mantle (Anderson 1989). Thus, the weak anomalies in the lower mantle could represent temperature anomalies of a similar magnitude to the strong anomalies in the upper mantle. However, it follows that the buoyancy of the lower mantle material would also be much less than that of the upper mantle material, because the effect of temperature on thermal expansion parallels its effect on seismic wave speeds. This argues against low-anomaly, lower mantle material forming the deeper part of a continuous, upwelling plume with high-anomaly, upper mantle material if significant flow is to occur within the lower mantle anomaly. Another argument against weak wave-speed anomalies representing lower mantle plumes is the observation of strong lower mantle anomalies elsewhere that have been called 'superplumes', for example, an anomaly that extends from the core–mantle boundary beneath the south Atlantic to the surface beneath the Afar hotspot (e.g. Ritsema *et al.* 1999; Megnin & Romanowicz 2000). The same reasoning that attributes plume-like temperatures to the weak anomalies beneath Iceland would attribute to such 'superplumes' temperature anomalies of ~ 1000 K, which are thought to be unlikely.

Other models focus on the possibility that the assumptions regarding the origin of the highest $^3He/^4He$ ratios may be wrong. It has been proposed that ^3He in erupted lavas may originate from cosmogenic ^3He that was added to the upper mantle along with siderophile elements during the latest stage of Earth accretion (the late veneer), although it is as yet unclear whether such helium could be subducted (e.g. Allegre *et al.* 1993; Anderson 1993; Farley & Neroda 1998). Variations in helium isotope ratios may reflect non-uniform distribution of U + Th in the upper mantle, which causes the $^3He/(U+Th)$ ratio to vary (Graham *et al.* 1996). Since ^4He is produced by the decay of U and Th, this would cause the $^3He/^4He$ ratio to vary. High $^3He/^4He$ ratios in some ocean island basalts (OIBs) and continental lavas thought to be plume-related may thus result from the preservation of some relatively high, old $^3He/^4He$ ratios by storage in a (U + Th)-depleted environment, a consequence of mantle inhomogeneity (Zindler & Hart 1986; Albarede 1998; Coltice & Ricard 1999; Anderson 2000b). Although this model removes the requirement for a little-degassed, primitive, high-^3He lower mantle source, it may retain the concept that high $^3He/^4He$ ratios originate in the lower mantle.

The existence of a primitive, little-degassed, high-^3He lower mantle is inconsistent with models of high-temperature planetary accretion and estimates of bulk Earth chemistry. Models that assume helium isotope ratios of >30 Ra in the lower mantle require chondritic abundances of ^3He there (e.g. Kellogg & Wasserburg 1990), which are at odds with the observation that the Earth is depleted in even less volatile noble gases. Such abundances are also at odds with the fact that the ^3He concentration in many high-$^3He/^4He$ hotspot rocks is much lower than that of MORB and, while it is generally assumed that this is caused by degassing as a result of shallow marine or subaerial eruption, the $^3He/^{22}Ne$ and $^4He/^{40}Ar$ ratios in such rocks suggest that they are not more degassed than MORB (Anderson 1998b,c, 2000a; Moreira & Sarda 2000). These observations suggest that the sources of hotspot rocks may be intrinsically low in ^3He, and bring into question the model that the highest $^3He/^4He$ ratios arise from a little-degassed, high-^3He lower mantle. The transport of large amounts of helium to the surface at hotspots is, in addition, at odds with the notion of a lower mantle that has remained primitive, isolated and isotopically distinct throughout geological time (e.g. Albarede 1998).

An alternative origin for the highest $^3He/^4He$ ratios might then be low ^4He, which might result from storage in (U + Th)-poor domains in the upper mantle, for example, depleted lithosphere, recycled lithosphere and dunite-rich domains (Anderson 1998b,c). Coincidence between (U + Th)-poor domains and those hotspots with high maximum values of $^3He/^4He$ is required by this model. It would be difficult for such domains to survive for the lengths of time necessary (up to 1 Gyr) in an upper mantle continually homogenized by vigorous convection. However, the upper mantle has not been homogenized by convection. Whole-mantle tomography shows great heterogeneity in the upper mantle, and shallow, buoyant, sublithospheric mantle may not be involved in convection. Furthermore, the apparent homogeneity of MORB, on which the homogeneous upper mantle model is based, may be a result of large-volume sampling of an inhomogeneous source (Anderson 2000b). Derivation of the highest $^3He/^4He$ ratios observed from (U + Th)-poor domains in the upper mantle is compatible with the tomographic images in that neither requires a lower mantle plume beneath Iceland.

It is of interest to reflect upon how the helium geochemistry of hotspot lavas correlates with the highly variable apparent depth extents of low-wave-speed anomalies observed using whole-mantle tomography. The maximum $^3He/^4He$ isotope ratios from the Iceland hotspot are among the highest measured anywhere on Earth (up to 37.7 Ra), yet the tomography provides little support for bulk mass advection from the lower mantle. On the other hand, the highest $^3He/^4He$ isotope ratios from volcanic provinces beneath which low-wave-speed anomalies are apparently continuous throughout the whole mantle, e.g. Afar and the Cook/Austral islands (Ritsema *et al.* 1999; Megnin & Romanowicz 2000), are lower than the highest from Iceland, with values of up to only 19 Ra for Afar (Marty *et al.* 1996) and 17 Ra for the Cook/Austral islands (Hanyu *et al.* 1999). The time is clearly ripe to couple investigation of $^3He/^4He$ ratios in lavas with other information such as possible tracers of core–mantle interaction (Pearson *et al.* 1999; Brandon *et al.* 2000), other geochemistry, surface tectonics and shallow processes, and to integrate cross-disciplinary observations to develop self-consistent, testable models.

4 CONCLUSIONS

Several independent seismic tomography experiments provide little support for a plume in the lower mantle beneath Iceland, but suggest that the Iceland hotspot is fed by an upwelling, most, if not all, of which is confined to the upper mantle. On the other hand, the very high $^3He/^4He$ ratios observed in some Icelandic rocks are traditionally considered to have a lower mantle source. Suggested ways in which these seemingly inconsistent results may be reconciled include a model involving a plume in the lower mantle that is too narrow to be detected by whole-mantle tomography, and a model whereby no plume exists and the high-$^3He/^4He$ ratios observed in some Icelandic rocks arise from the upper mantle.

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