Discussion of

Seismic observations of transition zone discontinuities beneath hotspot locations

by

Arwen Deuss

21st December, 2006, Don L. Anderson

The data in this paper show that there is no significant difference in transition zone (TZ) thicknesses between hotspot and non-hotspot regions. The average TZ thickness under hotspots is 237±10 km, which is within 0.5 σ of the global average. Yellowstone, Hawaii, Reunion and Easter have thicker TZ than the global mean, suggesting colder than average temperatures, at least for an olivine-dominated mantle. In general, however, the depths of the discontinuities and the TZ thicknesses show no correlation with hotspots. This elusiveness of plumes to seismic detection is usually attributed to the small size of plume tails and poor resolution (rather than to the absence of plumes). But other larger scale plume-related predictions can be tested. In particular, plumes and plume heads are predicted to spread out under the lithosphere and under the 650-km discontinuity–if it has a negative Clapeyron slope–and these features are well within the ability of surface waves and *SS*-precursors, respectively, to detect (e.g. Anderson et al., 1992a,b). Many authors have suggested that plumes originate from the so-called lower-mantle superplumes. If so, much of the mantle under Africa and the Pacific should have shallow 410-km discontinuities and warm transition regions. This does not seem to be the case.

It is useful to compare the means and standard deviations for the various data sets now available. The average thickness of the TZ for hotspots is 237±10 km; the global average is 242±20 km. From a statistical point of view, the two populations are indistinguishable. Thirteen hotspots were separated out as possible plumes. The TZ thickness for this subset is 234±13 km, essentially identical to the other two populations. Most of these hotspots have small swells and buoyancy fluxes (Courtillot et al., 2003) and can be related to tectonic features. If plumes originate in the lower mantle, the TZ should be particularly thin under the 'primary plumes' (Hawaii, Iceland, Easter, Afar and Reunion; see Courtillot et al., 2003; Anderson, 2005). The average TZ thickness for these is 243±9 km (Iceland data is from Du et al., 2006; Afar data from Nyblade et al., 2000). A transition zone thickness of 244 ± 19 km is obtained for the Afar region, consistent with the global average and with other hotspots. This suggests that the pronounced thermal anomaly beneath Afar that exists in the shallow mantle probably does not extend as far down as the transition zone (Nyblade et al., 2000). This is significant since the Afar is one of the highest scoring hotspots, as far as having strong plume credentials, and has some of the lowest upper mantle velocities in the world.

There is doubt regarding whether TZ thicknesses can be used as a thermometer, but the depth of the 410-km discontinuity has fewer complications and uncertainties. The average depth of this discontinuity for the 13 plume candidates is 417±6 km; the total hotspot list gives 411±9 km, statistically the same as the global average. The inferred temperature differences are small, about 75˚C (-100 to +250˚).

The author states that it is not possible to use *SS* data to draw general conclusions in favor or against the existence of plumes, but she may be too pessimistic. A long-lived plume will heat up the surrounding mantle over distances much greater than the nominal 100-150 km radius of a plume. In fact, some seismologists claim to see seismic evidence for many plumes (what they mean is, evidence for low velocity in the mantle, usually having lateral dimensions of >10˚). Some studies (see references in Deuss's paper) attribute all very large low-velocity regions to plumes. The features that are labeled 'plumes' in these papers have lateral dimensions of 10˚ to >20˚ at TZ depths. The fact that the *SS* data do not see variations in TZ thickness or '410' depths suggests that temperature variations are slight, certainly not plume-like. The present results can be used to rule out lateral spreading of plumes beneath the 650-km discontinuity and can rule out the high temperatures for the larger features that have been attributed to plumes because of their low seismic velocity. It is common to attribute lack of evidence for plumes to lack of resolution but it may be due to the absence of plumes.

Other studies (see references in Deuss's paper, and www.mantleplumes.org) have shown that the 650-km discontinuity is remarkably immune to variations in 410-km discontinuity depths, surface tectonics and magmatism, and upper mantle seismic velocities and inferred temperatures. The lack of a strong anticorrelation of discontinuity depths suggests that olivine is not the dominant TZ phase or that the high-temperature thermal anomalies inferred at shallow depths do not extend through the transition zone. A plausible interpretation of all of the data is that there are no large temperature excursions at TZ depths under surface hotspots or associated with low-seismic velocity-regions in the mantle. A developing consensus is that many seismic features are due to composition, not temperature. A minority view is that features that have been attributed to plumes may actually have a shallow origin and may be, in large part, due to lithology or high homologous temperature, not high absolute temperature. The present study supports that view.

26th January, 2007, Benoît Tauzin

Most seismic observations of the transition-zone discontinuities have been interpreted in terms of phase transitions in olivine. In the light of recent developments in high-pressure mineral physics, Deuss (this volume) proposes to include the effect of garnet in the interpretation. This effect is null on the 410-km discontinuity but can be important for the discontinuities at 520 and 660 km depths. Taking into account the garnet phase transition, almost any reasonable mantle transition zone (MTZ) thickness variation can be reconciled with a hot thermal plume, if the 410-km discontinuity is depressed. The author fairly states that *SS* wave data alone cannot be used to draw general conclusions in favor of, or against the existence of, plumes.

The author studied the 49 hotspot locations of the catalogue of Courtillot et al. (2003) using *SS* precursors. She observed robust precursors generated at the 410- and 660-km discontinuities beneath 26 stations. Among these 26 stations, two thirds showed evidence for a deepening of the 410-km discontinuity. The Clapeyron slope of the olivine phase transition at 410 km suggests that this deepening is compatible with a hot thermal anomaly. Such a hot thermal anomaly could be produced by a thermal plume, although a small anomaly that is not vertically continuous through the MTZ would produce the same effect.

SS precursor data have small amplitudes and are very sensitive to the approach used in their analysis. The author uses a bootstrap resampling technique to estimate uncertainties in the amplitude of the stacks. This technique can also be used to estimate errors in traveltimes. Gu et al. (2002) showed that, even in well-sampled regions, the traveltime uncertainties may occasionally reach 3 s (~ 10 km). This suggests that taking into account traveltime uncertainties might reduce the number of stations for which a deepening of the 410-km discontinuity is statistically significant.

The traveltime observations beneath hotspots are compared with a global average. Some studies report a thinner MTZ under oceans than beneath continents (-5 km compared with +8 km relative to the global average; Gu et al., 2002). As most of the studied hostposts are located in oceanic regions, one can wonder whether the observed traveltime anomalies would remain if compared with an oceanic average. Global *SS* precursor maps do not show evidence of MTZ thickness variations that might be associated with thermal plumes within Atlantic, Indian and Pacific oceans (Li et al., 2003).

One third of the observations show no evidence for a deepening of the 410-km discontinuity and remain to be explained. Some of these observations have traveltime differences (t_{ss}-t_{s410s}) close to the global average and may be attributed to a failure of *SS*-precursors to resolve narrow plume conduits. However, Cape Verde and Canary have t_{ss}-t_{s410s} traveltimes smaller than the global average (up to -5 s for Cape Verde). If correct, this indicates that either the mantle above the MTZ is much faster than average, or there is a strong, cold anomaly at 410 km depth which is picked up, despite the broad X-shaped Fresnel zone of *SS*-precursors. In both cases, this seems difficult to reconcile with the observation of a deep mantle plume by Montelli et al. (2006).

Currently, *SS* precursors and *Pds/Sdp* converted waves put better constraints on the thickness of the MTZ than on the absolute depths of discontinuities. If the effect of the garnet phase transition is significant, MTZ thickness measurements alone are unable to detect thermal plumes. Further experimental work is needed to estimate the relative contribution of olivine and garnet to the topography of the 660-km discontinuity. With new experimental results, and if future progress in seismic tomography allows us to estimate better the absolute depths of seismic discontinuities, there is a hope that *SS* precursors and *Pds/Sdp* datasets will become more accurate thermometers of the transition zone. In the meantime, many features of these datasets that are not explained yet could give additional constraints on upper mantle structure. For example, anomalous phases are sometimes observed just after the 410-km phase (see the negative polarities at the Azores, Comores and Easter in Figure 3 of Deuss, this volume). Similar features are observed on *Sdp* records (Vinnik et al. 2006) and suggest the existence of low-velocity anomalies within the transition zone.

27th January, 2007, Lev P. Vinnik

In my view, the seismic literature on plumes is heavily contaminated by controversial data. The main problem of *SS* precursors, a method which is very popular, is that lateral resolution of these data is low, perhaps a couple of thousand kilometers at best, and application of it to objects ten times smaller cannot bring anything but confusion. I doubt whether estimates of the thickness of the transition zone made by this method are correct for several reasons but mostly because *SS* is not the minimum time phase. Comparing the results of this method with another method (*Ps* converted phases in *P* receiver functions) revealed almost no correlation (Chevrot et al., 1999).

P receiver functions have better resolution, but this simple instrument can, in some hands, be harmful. Among results for plumes I would single out those obtained for Iceland, for at least two reasons. First, the data were analysed by at least two independent groups, and the tilted conduit and topography on the 660-km discontinuity reported by one group were not confirmed by another group (Du et al., 2006). Without independent checking, the tilted conduit and deformed 660-km discontinuity beneath Iceland claimed by the first group would have become favorite subjects for citation and imitation. Second, the network in Iceland is quite large, and there are several independent tomographic studies of the region. This means that topography on the 410-km discontinuity could be separated from the effects of volumetric velocity variations. In most other regions this opportunity is lacking.

Of course, tomography of Iceland was conducted by assuming that the mantle beneath 400 km is laterally homogeneous. This is certainly untrue, but the related effects have not been evaluated by anybody. Another approach to the problem of discontinuity topography is to measure the differential time between the *Ps* phases related to the 410- and 660-km discontinuities. The thickness of a hot transition zone and the related differential time should be small relative to the standard. This popular wisdom neglects the fact that the *P*- and *S*-wave velocities in the transition zone of hotspots could be anomalous also. The study of Du et al. (2006) demonstrates that this is of extreme importance for the issue of topography on the 660-km discontinuity. Unfortunately, sufficiently accurate data on velocities in the transition zone beneath most hotspots are unavailable.

Low-velocity layers in the transition zone and immediately above the 410-km discontinuity are very important for the plumes, but I don't know if these topics have been presented adequately. The author of a review paper should separate signals from noise in the literature, but this is difficult, both politically and scientifically.

27th January 2007, Don L. Anderson

The comments by Vinnik, earlier today, are valid but they do not change the conclusion of Deuss (this volume) and many previous studies that there is no correlation between transition zone (TZ) thickness and hotspots. This conclusion is based on many different phases and many different authors and methods. The only robust conclusion is that oceanic regions have a thinner TZ than continents and many subduction zones have thicker TZ (see http://www.mantleplumes.org/TransitionZone.html for references). Thus, TZ thickness joins heatflow and magma temperature as having little correlation with melting anomalies.

There are numerous reports of low velocity zones (LVZ) atop the 410- and 650-km discontinuities; these are quite consistent with eclogite sinkers being trapped at these depths (Anderson, this volume) but not with hot upwelling plumes. Hot plumes will spread out beneath endothermic phase changes, but not above phase boundaries. Low seismic velocities are consistent with eclogite or magma, but also with CO_2-bearing peridotite (Dean Presnall, personal communication). Low seismic velocity and high magma volume are not proxies for high absolute temperature or low density. Even if plumes are only 100-200 km across, their effect on the surrounding mantle, and their spreading out in the shallow mantle will affect the long-wavelength temperature and structure of the mantle (Morgan and Phipps Morgan, this volume; King and Redmond, this volume). On the other hand, the low seismic velocities of solid or partially molten eclogite blobs are not the result of excess absolute temperature, and their influence is relatively local. Eclogite blobs and peridotite infiltrated with eclogite melt can have low seismic velocities even if colder than ambient mantle.

All-in-all the seismic data are consistent with a top-down fertile blob model but not with a bottom-up thermal plume model.

1st February, 2007, Yu Jeffrey Gu

Global de-correlation of transition zone discontinuities has long been a mystery based on earlier studies of *SS* precursors (Shearer, 1993; Gu et al., 1998, 2003; Flanagan and Shearer, 1998). Explanation of this enigmatic result ranged from a poorly behaved 410-km discontinuity to inaccuracies in travel-time measurements and/or mantle shear velocity corrections. By systematically examining 49 hotspot locations (26 relatively well resolved), Deuss (this volume) underlines the critical effect of majorite-garnet phase transformation on the 660-km discontinuity. This hypothesis highlights the complexities within the transition zones and offers a viable explanation for the lack of a better anti-correlation between its two major phase boundaries.

The author introduces an important new criterion to determine the depth of origin of thermal plumes, emphasizing the topography of the 410-km discontinuity – the simpler of the two transition zone phase boundaries. This hypothesis combines preexisting knowledge about the exothermic phase change of olivine (Anderson, 1967) with statistically significant observations of a locally depressed 410-km discontinuity (as well as a normal-to-thin transition zone) at a substantial fraction (18 out of 26) of potential plume locations. The paper represents a key contribution to the identification and understanding of mantle plumes.

From a data perspective, this paper uses *SS* precursors as the main observables on the existence/vertical extent of thermal plumes. This choice is appropriate as the differential travel times of underside reflections can be highly sensitive to transition zone thickness, as well as to the vertical shear velocity at comparable depths beneath the mid points of the source-receiver pairs. However, questions have surfaced in recent years regarding the accuracy of the structure/topography inferred from *SS* precursors due to the mini-max nature of reflected waves and their wide Fresnel zones at long periods (Neele et al., 1997; Chaljub and Tarantola, 1997). Shearer et al. (1999) addressed some of the potential biases through a multi-scale resolution analysis. By inverting for synthetic differential travel times, they showed that a topographic inversion using long-period *SS* precursor observations is virtually immune to smaller-scale artifacts at a major subduction zone. That being said, a hot thermal mantle plume is more difficult to detect than a cold subducted oceanic lithosphere for at least two reasons:

1. a potentially smaller lateral dimension, and
2. the effect of wavefront healing.

The Fresnel zone of the *SS* precursors used in this study has a lateral dimension of 1000-1500 km, which is generally considered larger than the nominal resolution of a “primary” plume (Courtillot et al., 2003; Deuss, this volume). However, the “footprints” of the *SS* precursors are comparable to or smaller than “secondary” plumes beneath many hotspot locations. Even for some primary plumes/hotspots, for example, Iceland, high-resolution receiver function studies have shown reasonably coherent measurements of *Pds* (*d* for a discontinuity) across multiple bins that span ~1000 km laterally (Shen et al., 2003; Du et al., 2006). An anomaly of such dimensions can be effectively imaged by a targeted approach (Deuss, this volume) using *SS* precursors. The combination of heat dissipation from the ascending plume and the potential ponding of plume material at the base of the 660-km discontinuity (due to the endothermic phase transition of olivine) also aid long-period observations such as *SS* precursors. The effect of wavefront healing is difficult to gauge, though it is reasonable to assume that models generally underestimate the absolute values of velocity and discontinuity topography in the presence of hot thermal plumes.

The study of Deuss (this volume) finds approximately two-thirds of the 26 reasonably resolved hotspot locations with a depressed 410-km discontinuity and a normal or thinner transition zone. This general criterion for detecting mantle plumes could potentially benefit from high-resolution methods using receiver functions at, for example, the Hawaii hotspot. These different methods could be complementary, as recent global study by Lawrence and Shearer (2006) showed remarkable agreements between *Pds*- and *SdS*-derived transition zone thickness variations (Figure 1). Each method has its caveats. Low resolution remains the Achilles’ heel for *SS* precursors, though recent studies by Schmerr and Garnero (2006) and An et al. (personal communication) have shown some promise by utilizing small averaging caps (both studies), by including higher frequency signals (former study), and by introducing high-resolution Least-squares Radon Transforms (latter study). In the study of An et al. (personal communication), the preliminary topography measurements at 4 out of 5 primary hotspot locations satisfy the transition zone structure criterion proposed by Deuss (this volume). In comparison, *Sdp* or *Pds* waves can achieve a significantly greater resolution (100-500 km), though the interpretation of their arrival times is strongly influenced by both *P* and *S* velocities across a given discontinuity. Unfortunately, the *P* velocity resolution at transition zone depths remains to be desired. A bigger issue is data coverage, as *Pds* and *Sdp* waves solely rely on seismic station locations that are, at the present, largely continental.

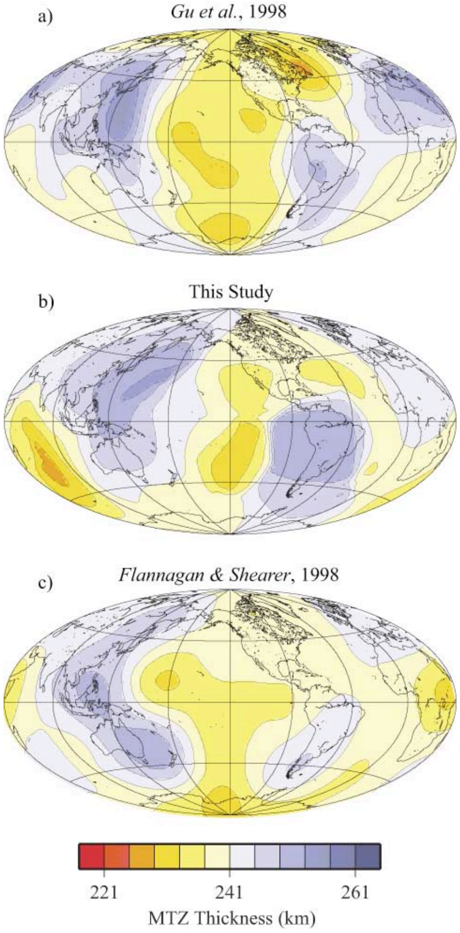

Figure 1. Smoothed maps of transition zone thickness for (a) Gu et al. (1998), (b) Lawrence and Shearer (2006), and (c) Flanagan and Shearer (1998). Reproduced from Lawrence and Shearer (2006) with the authors' permission.

The moral is that there is no “perfect” method for detecting and interpreting thermal plumes that consist of distinct types, chemical signatures and surface expressions. Until more ocean bottom seismographs are deployed around the world, *SS* precursors will continue to be one of the most effective global imaging tools to determine the existence/vertical extent of mantle plumes.

References

http://www.mantleplumes.org/TransitionZone.html

Anderson, D. L., 1967, Phase changes in the upper mantle, Science, 157, 1165-1173.

Anderson, D.L., 2005, Scoring hot spots: the plume and plate paradigms, in G.R.Foulger, J.H. Natland, D.C. Presnall and D.L. Anderson, eds., Plates, Plumes, and Paradigms, Geol. Soc. Am. Special Volume 388, 31-54.

Anderson, Don L., Tanimoto, T., and Zhang,Y.-S., 1992a, Plate tectonics and hotspots: The third dimension, Science, v. 256, p. 1645-1650.

Anderson, Don L., Zhang, Y.-S., Tanimoto, T., 1992b, Plume heads, continental lithosphere, flood basalts and tomography, in: Magmatism and the Causes of Continental Break-up, B. C. Storey, T. Alabaster and R. J. Pankhurst, eds., Geological Society Special Publication, No. 68.

Cevrot, S. I., L. Vinnik, and J.-P. Monttagner, Global scale analysis of the mantle Pds phases, JGR 104 (1999) 20203 - 20219.

Chaljub, E. and Tarantola, A., 1997, Sensitivity of SS precursors to topography on the upper-mantle 660-km discontinuity, Geophys. Res. Lett., 24, 2613-2616.

Courtillot, V., Davaille, A., Besse, J., and Stock, J.M., 2003, Three distinct types of hotspots in the Earth's mantle: Earth and Planetary Science Letters, v. 205, p. 295-308.

Du, Z. L.P. Vinnik and G.R. Foulger, Evidence from P-to-S mantle converted waves for a flat "660-km" discontinuity beneath Iceland, Earth Planet. Sci. Lettl, 241, 271-280, 2006.

Flanagan, M. F. and Shearer, P. M., 1998, Global mapping of topography on transition zone velocity discontinuities by stacking SS precursors, J. Geophys. Res., 103, 2673-2692.

Gu, Y. J., and A. M. Dziewonski (2002), Global variability of transition zone thickness, J. Geophys. Res., 107(B7), 2135, doi:10.1029/2001JB000489.

Gu, Y., Dziewonski, A. M., and Agee, C. B., 1998, Global de-correlation of the topography of transition zone discontinuities, Earth Planet. Sci. Lett., 157, 57-67.

Gu, Y. J., Dziewonski, A. M., and Ekström, G., 2003, Simultaneous inversion for mantle shear velocity and topography of transition zone discontinuities, Geophys. J. Int., 154, 559-583.

Lawrence, J. F. and Shearer, P. M., 2006, A global study of transition zone thickness using receiver functions, J. Geophys. Res., 111, B06307, doi:10.1029/2005JB003973.

Li, X., Kind, R., Yuan, X., Sobolev, S.V., Hanka, W., Ramesh, D.S., Gu, Y. & Dziewonski, A.M., (2003). Seismic observation of narrow plumes in the oceanic upper mantle, Geophys. Res. Lett., 30, 1334, doi:10.1029/2002GL015411.

Montelli, R., G. Nolet, F. A. Dahlen, and G. Masters (2006), A catalogue of deep mantle plumes: New results from finite-frequency tomography, Geochem. Geophys. Geosyst., 7, Q11007, doi:10.1029/2006GC001248.

Neele, F., de Regt, H., and Van Decar, J., 1997, Gross errors in upper-mantle discontinuity topography from underside reflection data, Geophys. J. Int., 129, 194-204.

Nyblade, A., Knox, R. & Gurrola, H., 2000, Mantle transition zone thickness beneath Afar: implications for the origin of the Afar hotspot, Geophysical Journal International, Volume 142, 615.

Schmerr, N, and Garnero, E. J., 2006, Investigation of upper mantle discontinuity structure beneath the central Pacific using SS precursors, J. Geophys. Res., 111, B08305, doi:10.1029/2005JB004197.

Shearer, P. M., Flanagan, M. F., and Hedlin, A. H., 1999, Experiments in migration processing of SS precursor data to image upper mantle discontinuity structure, J. Geophys. Res., 104, 7229-7242.

Shen, Y., Wolfe, C. J., and Solomon, S. C., 2003, Seismological evidence for a mid-mantle discontinuity beneath Hawaii and Iceland, Earth Planet. Sci. Lett., 214, 143-151.

Vinnik, L., and V. Farra (2006), S velocity reversal in the mantle transition zone, Geophys. Res. Lett., 33, L18316, doi:10.1029/2006GL027120.

Vinnik, L.P. and V. Farra, Low S velocity atop 410 km discontinuity and mantle plumes, submitted to EPSL (2007).