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Short communication

On the statistical significance of correlations between synthetic mantle plumes and tomographic models

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ABSTRACT

In a recent article, [Boschi, L., Becker, T.W., Steinberger, B., 2007. Mantle plumes: dynamic models and seismic images. Geochem. Geophys. Geosyst. 8, Q10006. doi:10.1029/2007GC001733] (BBS07) have reevaluated the degree to which slow seismic tomography anomalies correlate with the possible locations of plume-like mantle upwellings connected to surface hotspots. They showed that several, but not all, hotspots are likely to have a deep mantle origin. Importantly, they found that when advection of plume conduits in mantle flow is considered, such correlations are significantly higher than when conduits are assumed to be vertical under hotspots. The validity of these statements depends, however, on the definition of statistical significance. BBS07 evaluated the significance of correlation through simple Student's t tests. Anderson (personal communication, July 2007) questioned this approach, given that the true information content of published tomography models is generally unknown, and proposed, instead, to evaluate the significance of correlation by comparing tomographic results with Monte Carlo simulations of randomly located plumes. Following this approach, we show here that the correlation found by BBS07 between advected plumes and slow anomalies in S-velocity tomography is less significant than previously stated, but still significant (at the 99.7% confidence level). We also find an indication that the seismic/geodynamic correlation observed by BBS07 does not only reflect the natural tendency of plumes to cluster in slow/hot regions of the mantle: although realistically advected, and thereby biased towards such regions, our random plumes correlate with slow tomographic anomalies significantly less than the plume models of BBS07. A less significant correlation with plume models characterizes P-velocity tomography; the correlation is, however, enhanced, if flow is computed from tomographic models with amplified heterogeneity, possibly accounting for the known resolution limits of global seismic data. In summary, the conclusions of BBS07 are confirmed: even at relatively long wavelengths, tomographic models are consistent with the presence of a number of tilted, whole-mantle plume-shaped slow anomalies, connected to surface hotspots.

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1. Introduction

The plume concept was introduced by Morgan (1971) and Wilson (1973) to explain intraplate volcanism (hotspots) and age progressions along volcanic island chains. Since the early days, this concept has been modified substantially, e.g., by allowing for conduits that are distorted in mantle flow (Steinberger, 2000a; Steinberger et al., 2004). However, recently there has been much debate about the general validity of the plume hypothesis (e.g., Foulger and Natland, 2003; DePaolo and Manga, 2003; Sleep,

2006) and some authors have abandoned it (Anderson, 2000, 2005).

Rising thermal plumes would most likely lead to slow anomalies in seismic tomography maps, and many authors have evaluated the agreement between tomographic models and the location of plumes (e.g., Ray and Anderson, 1994; Seidler et al., 1999; Nataf, 2000; Becker and Boschi, 2002; Courtillot et al., 2003; Thorne et al., 2004). Boschi et al. (2007) (hereafter: BBS07) reviewed those findings, and applied a similarly minded analysis to most recent tomographic models. We now summarize BBS07's main observations and inferences.

BBS07 analyzed the most recent available tomographic models, estimating quantitatively how "plume-like" slow tomographic anomalies actually are. Using a "plume detector" algorithm

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(Labrosse, 2002; Zhong, 2006), they found that the number, length, and depth extent of slow, plume-like anomalies is strongly determined by parameterization choices, rather than, e.g., tomographic theory advances.

In the second part of their work, BBS07 determined several dynamic models of mantle-plume shape and location, and compared those to the same tomographic models. The plume models they considered included a vertical-plume one, where plumes are assumed to extend vertically downward from the hotspot locations compiled by Steinberger (2000a), and tilted-plume ones, where the distortion of plume conduits caused by their advection in mantle flow is determined in a two-step procedure, as described by Steinberger and Antretter (2006): first, large-scale mantle flow is computed from density anomalies based on the tomographic model smean, and on a prescribed viscosity profile; then, the motion of plume elements, with respect to initially vertical conduits, is computed as the vector sum of large-scale flow and depth-dependent buoyand rising speed. Plumes are assumed to form at the D", and constrained to reach the lithosphere, at the present day, at specific hotspot locations. Tilted-plume models considered by BBS07 included moving-source ones, where the plume source at the D" is displaced by mantle flow, and fixed-source ones, where this is not the case (Steinberger and Antretter, 2006). The moving-source, tilted-plume model of BBS07 is shown in their Fig. 2, bottom panel.

From this experiment, BBS07 found that tilted plume conduits are significantly better correlated with tomographic anomalies than vertical conduits, implying that physical models of plumes are partially confirmed by seismic tomography. They also found that this agreement is systematically better for moving-source than fixed-source plume models, with implications for thermochemical convection (McNamara and Zhong, 2004; Jellinek and Manga, 2002).

Last, BBS07 concluded that some, but not all, hotspots appear to have a lower mantle source, and a continuously imaged conduit consistent in shape and location to the corresponding predictions of flow models.

All these statements are contingent upon the definition of statistical significance. The statistical significance of the correlation between two functions depends, through Student's t test (e.g., Press et al., 1993), on the total number N of "free" parameters that describe the two functions. Although the number of basis functions (voxels, splines, spherical harmonics...) parameterizing a tomographic model is known, this number does not coincide with N, as model coefficients are typically coupled by smearing (an effect of limits in the geographic coverage of the data) and regularization (needed to counter the effects of random noise in the data). N equals, rather, the trace of the resolution matrix (e.g., Tarantola, 2005), which is very expensive to compute, and typically not provided (not known) by tomography authors (Boschi, 2003).

BBS07 (see their Section 3.2.1) translated all models to a consistent spherical harmonic parameterization, with maximum harmonic degree L = 63, chosen arbitrarily but large enough to appropriately describe all tomographic and geodynamic images. They then eluded the problem of quantifying resolution, setting N to the corresponding number $(L + 1)^2 = 64^2$ of independent harmonic coefficients. They did note that "a lower number of degrees of freedom, close to more conservative estimates of tomographic resolution (i.e., highest harmonic degree ~ 20)", would have resulted in a lower significance of found values of correlation (but still above 90% significance if $N = 21^2$).

We complement here the analysis of BBS07 with estimates of significance independent of *N*; namely, as suggested by Anderson (personal communication, July 2007) in response to BBS07, we generate random models of plume conduits, and calculate their correlation with tomographic results. After many realizations of this

experiment, we use the distribution of the resulting correlation values to estimate correlation significance. We explore how estimates of significance are affected by the statistics of modeled random plumes (age, tilt).

We additionally compute the correlation of slow anomalies from tomographic models, at all depths, with the surface location of spreading centers. Since spreading centers are known to be the surface expression of an uppermost-mantle phenomenon, they should not correlate with slow seismic anomalies at depths larger than the shallow mantle, and could so be considered for a null-hypothesis test (Ray and Anderson, 1994).

Last, we evaluate how mantle flow modeling, and therefore our models of plume conduits and their similarity to tomography, could be affected by an underestimate of the density heterogeneity driving mantle flow. This is a problem that our method is likely to suffer from, since we scale density heterogeneity from tomography models with limited resolution.

2. Significance of correlation

We re-evaluate the significance of the correlation between tomographic models and physical models of mantle-plume location and shape, comparing it to the correlation between the same tomographic models and randomly generated plume models. We complement this exercise with a null-hypothesis test, where we calculate the correlation between mantle tomography and the distribution of spreading centers at the surface.

2.1. Realizations of random plume models

To generate each single random model of advected plume conduits, we first generate a random map of vertical plumes. We set the initial locations of 44 plumes (as many as listed by BBS07) to 44 points, randomly picked with constant probability density over the whole solid angle. Plume-age (i.e., the time at which the computation is started with an initially vertical plume conduit) is then likewise picked randomly with uniform probability between 0 and 120 Ma, roughly corresponding to average plume age \approx 70 Ma in Steinberger (2000a) and BBS07, and to the fact that the oldest hotspot track linked to an active hotspot extends to about 130 Ma. We set the anomalous mass flux associated with a plume to 10³ kg/s (BBS07) (we find that plume models do not strongly depend on the value of this parameter). We apply the mantle-flow model of Steinberger and Antretter (2006) and BBS07, based on the seismic S model smean of Becker and Boschi (2002), to compute the tilt of the initially vertical plumes, due to advection. Plumes are not required to reach any specific location at the Earth's surface.

The resulting models of plume conduits are geographically uncorrelated with the physical ones of Steinberger and Antretter (2006) and BBS07, but share their general properties (plume width, maximum plume tilt, etc.). We follow the same procedure of BBS07 (Section 3.2.1) to expand plume conduit models into spherical harmonics at ten depth layers, with maximum harmonic degree $\ell = 40$ for computational efficiency. We repeat this process 5000 times, to obtain as many independent random plume models.

We additionally generate random plume models with vertical conduits. We pick, again, 44 locations on the surface of the Earth from a uniform, random distribution, and, neglecting the effects of mantle flow, we associate to each of them a vertical plume conduit extending down to the CMB. Again, we expand the corresponding spatial fields into harmonics (maximum $\ell = 40$) at ten depth layers. We repeat this process 5000 times.

Last, we generate two smaller sets of \sim 400 random plume models, designed to measure the effects of age and tilt of random plumes

on our new estimates of correlation significance (experiments with populations of 5000 described above showed us that a set of 400 random models is sufficient to achieve fairly stable distributions of correlations). Plumes are generated randomly as above, but with relaxed limits on age, now ranging between 0 and 210 Ma. We next organize them in subsets, based on the amount of tilt they develop. A first model set ("straight and young") is then assembled by forming 44-plume models that do not include plumes tilted more than 60° or older than 120 Ma (same age limit as above); the second model set ("straight and old") includes 44-plume models with plumes also $\leq 60^{\circ}$ tilted, but 0–210 Ma old. These last model sets serve to evaluate how our estimates of correlation significance are affected by the inherent tendency even of random plume models to (1) be advected toward regions of presumed upwelling (i.e., slow regions of smean), and (2) survive for a longer time in those regions (Steinberger and O'Connell, 1998): both these modeling effects tend to increase the correlation between tomography and plume models which are in turn based on tomography (BBS07).

2.2. Significance of correlation between tomography and dynamic plume models

For each random plume-conduit model set, we compute the correlation r_{20} , up to $\ell = 20$, between each plume model, and a suite of

tomographic models (negative anomalies only, BBS07 for details), at all parameterized depths in the mantle. (We verified that correlations remain significant after including harmonic coefficients of degree $\ell > 20$, and that harmonic degrees ≤ 5 are responsible for the largest contribution to correlation.) Included tomographic models are the most recently published ones, plus *smean* and *pmean* summarizing earlier results; models analyzed by BBS07, all isotropic, are complemented with the Voigt averages (e.g., Ekström and Dziewoński, 1998) of two radially anisotropic ones (*s*362*wmani* of Kustowski et al., 2006, *saw*642*an* of Panning and Romanowicz, 2006).

We show the results of our analysis in Figs. 1 and 2. With the exception of model vox5p07, details on specific models can be found in the references provided in captions. We derived model vox5p07 in much the same way as vox3p (BBS07), but with a slightly coarser (5° rather than 3° pixels) parameterization, and inverting not only P, but also *PKPbc*, *PKPdf* (core-refracted) and *PcP* (core-reflected) travel-time data from the International Seismological Centre (ISC) bulletins (Antolik et al., 2001). Model vox5p07 is similar to the preferred isotropic model of Soldati et al. (2003), but was selected after a more careful evaluation of trade-offs between different parameterization/regularization in different regions of the Earth (Soldati et al., 2006). Like vox3p, model vox5p07 is characterized by a small-scale, plume-cluster- (Schubert et al., 2004)



Fig. 1. Each panel shows the correlation r_{20} as a function of depth (vertical axis) and up to harmonic degree $\ell = 20$ between one shear-wave (S) tomography model (negative anomalies only, see BBS07): (green lines) spreading centers (null hypothesis test); (blue) vertical plumes located under known hotspots; (red) modeled advected plumes (with moving source at the CMB) from BBS07. Grey dashed lines indicate the $\pm 2\sigma$ levels for correlations with 5000 Monte Carlo vertical plume models. Long-dashed dark red lines indicate the mean correlation with 5000 Monte Carlo advected plume models; from those, four example histograms at different layer depths are shown; the corresponding $\pm 2\sigma$ levels for the same models are denoted by short-dashed, dark red lines. Top left: *smean* (Becker and Boschi, 2002); top center: *tx*2007 (Simmons et al., 2006); bottom right: *saw*642*an* (Panning and Romanowicz, 2006).



Fig. 2. Same as Fig. 1, but compressional-wave (P) models. Top left: *pmean* (Becker and Boschi, 2002); top center: *vox5p*07 (this study); top right: *pri* – *p*05 (Montelli et al., 2006); bottom left: *hsml-p* 06 (Houser et al., 2008); bottom center: *mitp*07 (Li et al., 2007). The yellow and pink curves in the top center panel denote the correlation between slow anomalies from *vox5p*07, and a plume conduit model based on *vox5p*07itself, before and after scaling as discussed in Section 3.2(all other plume models, like those of Fig. 1, are based on *smean*).

rather than superplume-type distribution of slow anomalies in the central-Pacific lowermost mantle.

From both Figs. 1 and 2 it is immediately apparent that the mean correlation (long-dashed, dark red lines) between tomography and random, advected plume-conduit models grows with increasing depth. This effect is explained in terms of the theory of plume formation and growth described by Steinberger and Antretter (2006), and applied here to model the distortion of "random" plumes (see also Section 2.1 above): plumes are advected by mantle flow, and as they form (even if they form at completely random locations over the CMB surface) they are "attracted" towards the "hot", low-velocity regions of the assumed Earth model *smean*, where their sources eventually converge (Gonnermann et al., 2004).

Figs. 1 and 2 also show that values of correlation between random plume models and tomography are distributed normally. We can compute, at each depth and for each model, the standard deviation σ of such a distribution, and use it to estimate the (twosided) significance of correlation: it is a property of the normal distribution that, e.g., 95.45% of the observed values of a normally distributed quantity are within the $\pm 2\sigma$ range, and it can be inferred that a correlation that falls outside the $\pm 2\sigma$ range is significant at the 95.45% level. We thus find that higher values of correlation are needed to achieve the same level of significance, with respect to those inferred from BBS07's statistics. As explained in Section 1, this expected finding reflects BBS07's overestimate of the unknown number *N* of free parameters describing tomographic models. The analysis we conduct here does not depend on *N*, and is therefore more reliable.

Despite these provisos, correlations between dynamically modeled advected plumes (specifically, the moving-source model of BBS07, illustrated in the bottom panel of their Fig. 2) and all tomographic models in Fig. 1(solid red curves) are, in most of the mantle, above the 2σ significance level, inferred from the distribution of Monte Carlo plumes (short-dashed, dark red curves). In most of the lower mantle, correlation is above or close to the 3σ level, equivalent to 99.74% significance. The results of BBS07 are therefore confirmed. Values of correlations below 2σ -significance are more frequent for P models in Fig. 2, confirming, again, BBS07's findings (see in particular their Figs. 9 and 13). Differences between P and S models in the lower mantle are normally found at harmonic degrees $\ell > 6$ (Becker and Boschi, 2002),0 and possibly reflect the different nature of seismic observations from which the models are derived: P models are almost exclusively based on travel-time picks (equivalent to "infinite-frequency" waves), S ones on a wider variety of data, including surface-wave waveforms (resulting in a much better constrained upper mantle) and measures of body-wave cross-correlations (e.g., Bolton and Masters, 2001), with sensitivity kernels accordingly extending over larger volumes (Montelli et al., 2004). Different sensitivities of P and S velocities to chemical heterogeneities will also play a role (Masters et al., 2000).

We have also computed the correlation between tomography and the random models of *vertical* plumes described in Section 2.1,



Fig. 3. Same as Figs. 1 and 2, but plume models only include relatively less tilted plumes. The left panel illustrates results from the model set we dubbed "straight and young" (310 models); the right panel refers to "straight and old" plume models (424 models). The latter are, by construction, most biased toward tomography. For simplicity, only results from model *smean* are shown.

and we have found that its mean values are all approximately constant (close to zero) with respect to depth. The corresponding $\pm 2\sigma$ values are shown as dashed grey curves in Figs. 1 and 2. Except for the uppermost mantle, the σ of tomography vs. vertical-random-plume correlations (dashed grey lines) is always less than that of tomography vs. advected-random-plume correlations (dashed dark red lines). This difference reflects the amount by which correlation between computed plume conduits and tomography is generated by the advection of plume conduits towards slow anomalies.

2.3. Implications of the age and tilt of random plumes

We derive histograms like those in Figs. 1 and 2, from the "straight and old" and "straight and young" sets of plume models described at the end of Section 2.1. Strongly tilted plumes, which are mainly found in regions of fast/cold downwellings, and thus tend to reduce dynamic/tomographic model correlation, are excluded from these model sets. Random "straight" plume models are then systematically better correlated with tomography than models with unconstrained plume tilt. As a result, the σ values (and estimated thresholds of significance) of correlation determined from both the "straight and old" and "straight and young" random model sets are generally larger than those in Figs. 1 and 2.

This effect is very small in the case of "straight and young" plume models (left panel of Fig. 3), with correlation still above the 2σ level, and close to 3σ , at most depths. "Old" plumes (age up to 210 Ma; right panel of Fig. 3) are more strongly biased toward regions of low seismic velocity, and the estimates of σ resulting from the "straight and old" plume model set accordingly larger. For most tomographic models, correlation significance at most depths is below the thus estimated 2σ level (but always above the σ level).

BBS07 recognized that there is an element of circularity in comparing, as they did, tomography with dynamic models that are themselves based on tomography: plumes are advected by mantle flow, and mantle flow is driven by density anomalies which are in turn estimated on the basis of tomography; modeled plumes are then biased to resemble the geographic pattern of slow/hot tomographic anomalies. The correlation found by BBS07 between tomography and plumes must then be explained, at least partly, by this bias. The experiments we describe here help to separate out physically meaningful similarities. The advection of our randomly generated plumes is not random, but driven, just like that of BBS07's "realistic" plumes, by *smean*-based mantle flow. We have verified (Section 2.2) that this is not sufficient to reproduce the high correlations found by BBS07: correlations between tomography and our random plumes are systematically significantly lower (compare the histograms with the solid red curves in Figs. 1–3).

Excluding from our random plume models plumes that are particularly strongly tilted (hence probably originating from regions of cold/fast lowermost mantle, and then advected to hot/slow regions), and allowing included plumes to be very old, we have modeled random plumes even more strongly biased toward the assumed tomographic model. The correlation between random plumes and tomography is, thus, increased, but, importantly, is still significantly lower than that between tomography and "realistic" plume models. We infer that the levels of correlation found by BBS07 between "realistic" plumes and tomography are not simply the result of circular reasoning, but reflect a true similarity.

2.4. "Physical" null-hypothesis test

The significance of tomography-dynamics similarities can be alternatively evaluated by comparing correlations found by BBS07 to the correlation of slow tomography anomalies with a geophysical observable not physically related to them: a null-hypothesis test. Based on simple geodynamic considerations, the geographic distribution of spreading centers should not be correlated with that of hotspots and plume conduits, or, in general, with slow tomography anomalies, except for those in the uppermost mantle. Following Ray and Anderson (1994), we construct a spherical harmonic representation of spreading center locations, and use it for a null-hypothesis test. We first discretize the spreading centers of the NUVEL-1 model (DeMets et al., 1990); then, in analogy to the plume expansions (BBS07), we generate a spatial field that is unity within 200 km distance from a ridge, and zero elsewhere. We expand into harmonics up to $\ell = 40$ using a cos² taper to minimize ringing, and compute correlation up to harmonic degree $\ell = 20$.

Green curves in Figs. 1 and 2 show correlations between slow tomographic anomalies and the spreading center "null hypothesis" of Ray and Anderson (1994). For all models, there is almost no correlation in the lower mantle below \sim 1000 km depth. The maximum depth to which correlation is significant ranges for most models between ~ 200 and ~ 700 km, somewhat deeper than what might be expected underneath ridges for passive spreading: this is probably an effect of smearing of true anomalies due to poor seismic coverage of the transition zone. Correlation remains significant down to larger depths (\sim 1000 km) for models pri - s05 and pri - p05(Montelli et al., 2006), in agreement with the generally high radial correlation of those models discussed by Boschi et al. (2006). It is particularly small, conversely, for the two radially anisotropic models we considered, s362wmani and saw642an: this suggests that accounting for lateral variations in radial anisotropy improves resolution and reduces vertical smearing, at least for the upper mantle.

3. Performance of different tomographic models as predictors of plume location

Albeit statistically significant, the correlations we find are far from perfect. We investigate whether correlation could be improved by generating new plume models after computing mantle flow on the basis of tomographic models other than *smean*. We first employ the P model *vox5p*07, characterized (like most P models) by relatively strong short-scalelength structure at the bottom of the mantle, where S models are smoother. As an additional, independent exercise, we study changes in plume-tomography correlations when plumes are derived from virtual P and S models obtained after multiplying *vox5p*07 and *smean* by arbitrary factors.

3.1. Modeling mantle flow on the basis of P-velocity tomography

BBS07 derived advected plume conduits from a mantle-flow model based on tomography model *smean*; they then compared the same plume-conduit model to all tomographic images. This was a legitimate procedure, because (i) BBS07 were only interested in the general plume-ness of slow tomographic anomalies, and not in the performance of different tomographic models as predictors of plume location, and (ii) recent tomographic models are characterized by very similar long-spatial-wavelength patterns (e.g., Becker and Boschi, 2002), most important to predict the displacement and final location of plume sources. *smean* was preferred by BBS07 after it was proved to lead to the best match of geodynamical (Steinberger and Calderwood, 2006) and seismological (Qin, 2007) observables.

In the assumption that the plume paradigm is correct, one might want to take a further step forward, and measure how consistent the geographic distribution of plumes as deduced from different tomographic models is with the dynamically modeled shape and location of plumes. This exercise requires that mantle flow, and



Fig. 4. Mantle plume models are determined based on mantle flow computed from differently scaled versions of *smean*, and the resulting correlations with S (left panels) and P (right panels) tomography are plotted as functions of the scaling factor. Correlations with different tomographic models are denoted by different colors, as specified in the figure. We average correlations over all lower-mantle depths (top panels), and over the bottom ~900 km of the mantle only (bottom panels). A dashed grey horizontal line marks the 2σ significance level. The "RMS plume misfit", or the root mean square distance (in degrees) between modeled and observed hotspots, is plotted as a solid grey line.

subsequently the advection of plumes, be calculated independently from all tomographic models to be compared. We can then evaluate the correlation between each tomographic model, and dynamic plumes computed on the basis of that model.

We scale P-velocity anomalies from model vox5p07, to make an estimate for density anomalies, in the usual assumption that they be of purely thermal origin. Consistently with the work of Steinberger and Calderwood (2006), a depth-dependent ratio between density and P velocity is determined as follows: the anharmonic contribution for the upper mantle is adopted from Goes et al. (2004); the anelastic contribution is computed assuming an infinite *Q*-factor for purely compressional motion; for the lower mantle, we follow Steinberger and Holme (2008). With the same procedure as Steinberger and Antretter (2006) and BBS07, we then model mantle flow on the basis of the resulting density model, and use it to determine 44 plume conduits, associated with the 44 hotspots of BBS07.

The subsequently computed correlation between this plume model and slow anomalies from *vox5p*07 is shown as a yellow line in Fig. 2(top center panel). This correlation is everywhere lower than that between *smean* and our *smean*-based plume conduit model (top left panel of Fig. 1), and close to that between the latter and *vox5p*07. We infer that, despite its higher nominal resolution, *vox5p*07 is not, in the plume paradigm, a better model than *smean*. Based on the analysis of Becker and Boschi (2002), these statements probably apply to all current P models, when compared to S ones.

3.2. Modeling mantle flow on the basis of arbitrarily scaled P and S models

Besides our neglect of mineral-physics and compositional effects, the validity of our plume models is naturally limited by inac-

curacies in the tomographic models used to estimate the density distribution that drives mantle flow (BBS07). One known deficiency of tomographic models is their tendency to underestimate the true amplitude of seismic velocity anomalies (e.g., Boschi, 2003). To address this issue, we multiply *smean* and *vox5p*07 by a factor, compute the corresponding mantle flow and plume models, and evaluate the correlation of the latter with tomography: we repeat this procedure for a range of values of the scaling factor. The results are summarized in Figs. 4 and 5.

Tomographic models with the same pattern as *smean* or *vox5p*07, but smaller amplitude, lead to plume models that are less well correlated with tomography. Correlation decreases with decreasing scaling factor. Conversely, tomographic models of larger amplitude often predict plume models that are better correlated with tomography. The growth in correlation with increasing scaling factor is minor or non-existent if the flow is computed from scaled versions of model *smean* (Fig. 4); it is significant if the flow is computed from the P model *vox5p*07 (Fig. 5).

As the scaling factor is increased, increasingly large density anomalies cause plume conduits to be more strongly tilted, to the point that an increasing number of modeled plumes are not connected to surface hotspots. To monitor this effect, we calculate, and show in Figs. 4 and 5, the root mean square distance between modeled and observed hotspot locations. As this "plume misfit" grows, plume models cease to be realistic, and the correlation vs. scalingfactor curves in Fig. 4 become wiggly and noisy. To observe a similar effect in the curves of Fig. 5, we would need to consider slightly larger values of the scaling factor.

Within the plume paradigm, and assuming that the velocity/density scaling applied (Steinberger and Calderwood, 2006) is adequate, one interpretation of Figs. 4 and 5 is that the amplitude



Fig. 5. Same as Fig. 4, but mantle flow is now computed from differently scaled versions of the P model vox5p07.

of tomographically mapped velocity anomalies is systematically underestimated (e.g., Boschi, 2003): correcting this error through the application of a scaling factor then improves correlation between plume distribution as predicted from the assumed, scaled velocity model, and the pattern of tomography itself. The fact that larger values of the scaling factor are needed for P models is consistent with the idea that P-velocity heterogeneities are underestimated by tomography more severely than S-velocity ones. Underestimation of seismic anomalies by a factor \sim 2 is consistent with the results of, e.g., Boschi and Dziewoński (1999) and Boschi (2003).

We show in Fig. 2(pink curve, top center panel) the correlation at all depths between vox5p07, and a plume model determined on the basis of vox5p07, scaled so as to optimize correlation, while remaining in a regime where modeled and observed hotspot locations are approximately coincident (scaling factor ~ 2 based on Fig. 5, right panels). There is a visible improvement with respect to results based on unscaled "*smean*-driven" (red curve) or "*vox5p*07-driven" plumes (yellow curve).

The loss of correlation with decreasing scaling factor in Figs. 4 and 5 indicates that, in the plume paradigm, convection models where flow is partly explained by density heterogeneities ("active" up- and down-wellings) explain tomography better than convection models entirely driven by plate motions. Reducing the scaling factor is, in fact, equivalent to diminishing the contribution of density anomalies, while that of plate motions remains unchanged.

4. Conclusions

Our tests confirm that the conclusions of BBS07 are robust in a statistical sense: low S-velocity anomalies are where we would expect them in the lower mantle, according to advected plume models with moving plume sources (Steinberger and Antretter, 2006). Below ~1200 km, correlation $|r_{20}| \gtrsim 0.4$ is of the same order as, for example, the match found by Becker and Boschi (2002) between global subduction reconstructions (Steinberger, 2000b; Lithgow-Bertelloni and Richards, 1998) and seismic tomography. Even after the Monte Carlo test conducted here, more reliable than BBS07's theoretical analysis, the significance of the mentioned correlation is above or close to 3σ . It can be further increased, if mantle plumes are modeled on the basis of "amplified" versions of smean, i.e., obtained multiplying smean velocity anomalies by a factor >1. With the latter exercise, described in Section 3.2, we attempt to account for the underestimation of the amplitude of anomalies, inherent to global seismic tomography (e.g., Boschi, 2003). In the plume paradigm, this finding additionally implies that density anomalies play an important role, compared to plate motions, in defining the character of mantle flow.

We also confirm BBS07's finding that the similarity of plume models to P tomography is systematically less significant than their similarity to S tomography. The correlation between plumes and P tomography models does not improve much, even when we assume a P model (*vox5p07*) as the starting point for the modeling of mantle flow and plume advection (Section 3.1). Scaling *vox5p07* before modeling mantle flow and plume conduits leads to an increase of the correlation, which however remains lower than that found applying the same procedure with *smean* as starting model, and equal values of the scaling factor.

The partial disagreement of results obtained from S and P tomography is consistent with the decorrelation, at harmonic degrees $\ell > 6$, between global P and S tomography of the lowermost mantle (e.g., Masters et al., 2000). This discrepancy might, in turn, reflect the different sensitivity of typical P vs. S data to Earth structure, or the different relation between P and S velocity heterogeneities, and chemical heterogeneities in the mantle.

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References

- Anderson, D.L., 2000. The thermal state of the upper mantle: no role for mantle plumes. Geophys. Res. Lett. 27, 3623–3626.
- Anderson, D.L., 2005. Scoring hotspots: the plume and plate paradigms. In: Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L. (Eds.), Plates, Plumes, and Paradigms, vol. 388. Geological Society of America Special Paper, pp. 31–54.
- Antolik, M., Ekström, G., Dziewoński, A.M., 2001. Global event location with full and sparse data sets using three-dimensional models of mantle P-wave velocity. Pure Appl. Geophys. 158, 291–317.
- Becker, T.W., Boschi, L., 2002. A comparison of tomographic and geodynamic mantle models. Geochem. Geophys. Geosyst. 3 (2001GC000168).
- Bolton, H., Masters, G., 2001. Travel times of P and S from the global digital networks: implications for the relative variation of P and S in the mantle. J. Geophys. Res. 106, 13527–13540.
- Boschi, L., 2003. Measures of resolution in global body-wave tomography. Geophys. Res. Lett. 30 (2003GL018222).
- Boschi, L., Becker, T.W., Soldati, G., Dziewoński, A.M., 2006. On the relevance of Born theory in global seismic tomography. Geophys. Res. Lett. 33 (2005GL025063).
- Boschi, L., Becker, T.W., Steinberger, B., 2007. Mantle plumes: dynamic models and seismic images. Geochem. Geophys. Geosyst. 8, Q10006, doi:10.1029/ 2007GC001733.
- Boschi, L., Dziewoński, A.M., 1999. 'High' and 'low' resolution images of the Earth's mantle—implications of different approaches to tomographic modeling. J. Geophys. Res. 104, 25567–25594.
- Courtillot, V., Davaille, A., Besse, J., Stock, J., 2003. Three distinct types of hotspots in the Earth's mantle. Earth Planet. Sci. Lett. 205, 295–308.
- DeMets, C., Gordon, R.G., Argus, D.F., Stein, S., 1990. Current plate motions. Geophys. J. Int. 101, 425–478.
- DePaolo, D.J., Manga, M., 2003. Deep origin of hotspots—the mantle plume model. Science 300, 920–921.
- Ekström, G., Dziewoński, A.M., 1998. The unique anisotropy of the Pacific upper mantle. Nature 394, 168–172.
- Foulger, G.R., Natland, J.H., 2003. Is "hotspot" volcanism a consequence of plate tectonics. Science 300, 921–922.
- Goes, S., Cammarano, F., Hansen, U., 2004. Synthetic seismic signature of thermal mantle plumes. Earth Planet. Sci. Lett. 218, 403–419.
- Gonnermann, H.M., Jellinek, A.M., Richards, M.A., Manga, M., 2004. Modulation of mantle plumes and heat flow at the core mantle boundary by plate-scale flow: results from laboratory experiments. Earth Planet. Sci. Lett. 226, 53–67.
- Houser, C., Masters, G., Shearer, P.M., Laske, G., 2008. Shear and compressional velocity models of the mantle from cluster analysis of long-period waveforms. Geophys. J. Int., inpress.
- Jellinek, A.M., Manga, M., 2002. The influence of a chemical boundary layer on the fixity, spacing and lifetime of mantle plumes. Nature 418, 760–763.
- Kustowski, B., Dziewoński, A.M., Ekström, G., 2006. Modeling the anisotropic shearwave velocity structure in the Earth's mantle on global and regional scales. Eos Trans. AGU 87 (52) (Fall Meet. Suppl., Abstract S41E-02).
- Labrosse, S., 2002. Hotspots, mantle plumes and core heat loss. Earth Planet. Sci. Lett. 199, 147–156.
- Li, C., van der Hilst, R.D., Engdahl, E.R., 2007. A new global model for P wavespeed variations in Earth's mantle. Geochem. Geophys. Geosyst., in preparation.
- Lithgow-Bertelloni, C., Richards, M.A., 1998. The dynamics of Cenozoic and Mesozoic plate motions. Rev. Geophys. 36, 27–78.
- Masters, G., Laske, G., Bolton, H., Dziewoński, A.M., 2000. The relative behavior of shear velocity, bulk sound speed, and compressional velocity in the mantle: implications for chemical and thermal structure. In: Karato, S.-I., Forte, A.M., Liebermann, R.C., Masters, G., Stixrude, L. (Eds.), Earth's Deep Interior. Mineral Physics and Tomography from the Atomic to the Global Scale. Geophysical Mongraphy, vol. 117. AmericanGeophysical Union, Washington, DC, pp. 63–87.
- McNamara, A.K., Zhong, S., 2004. The influence of thermochemical convection on the fixity of mantle plumes. Earth Planet. Sci. Lett. 222, 485–500.
- Montelli, R., Nolet, G., Dahlen, F.A., Masters, G., 2006. A catalog of deep mantle plumes: new results from finite-frequency tomography. Geochem. Geophys. Geosyst. 7, Q11007.
- Montelli, R., Nolet, G., Masters, G., Dahlen, F.A., Masters, G., Hung, S.-H., 2004. Global P and PP traveltime tomography: rays versus waves. Geophys. J. Int. 158, 637–654.
- Morgan, J.P., 1971. Convection plumes in the lower mantle. Nature 230, 42–43. Nataf, H.-C., 2000. Seismic imaging of mantle plumes. Annu. Rev. Earth Planet. Sci. 28, 391–417.
- Panning, M.P., Romanowicz, B.A., 2006. A three dimensional radially anisotropic model of shear velocity in the whole mantle. Geophys. J. Int. 167, 361–379.

- Press, W.H., Teukolsky, S.A., Vetterling, W.T., Flannery, B.P., 1993. Numerical Recipes in C: the Art of Scientific Computing, second ed. Cambridge University Press, Cambridge.
- Qin, Y., 2007. SPICE benchmark pour mèthodes tomographiques globaux et test des modèles tomographiques globaux. Ph.D. Thesis. Institut de Physique du Globe, Paris.
- Ray, T.R., Anderson, D.L., 1994. Spherical disharmonics in the Earth sciences and the spatial solution: ridges, hotspots, slabs, geochemistry and tomography correlations. J. Geophys. Res. 99, 9605–9614.
- Schubert, G., Masters, G., Olson, P., Tackley, P., 2004. Superplumes or plume clusters? Phys. Earth Planet. Int. 146, 147–162.
- Seidler, E., Jacoby, W.R., Cavsak, H., 1999. Hotspot distribution, gravity, mantle tomography: evidence for plumes. J. Geodyn. 27, 585–608.
- Simmons, N.A., Forte, A.M., Grand, S.P., 2006. Constraining mantle flow with seismic and geodynamic data: a joint approach. Earth Planet. Sci. Lett. 246, 109–124.
- Sleep, N., 2006. Mantle plumes from top to bottom. Earth Sci. Rev. 77, 231-271.
- Soldati, G., Boschi, L., Piersanti, A., 2003. Outer core density heterogeneity and the discrepancy between PKP and PcP travel time observations. Geophys. Res. Lett. 30 (2002GL016647).
- Soldati, G., Boschi, L., Piersanti, A., 2006. Global seismic tomography and modern parallel computers. Ann. Geophys. 49, 977–986.
- Steinberger, B., 2000a. Plumes in a convecting mantle: models and observations for individual hotspots. J. Geophys. Res. 105, 11127–11152.
- Steinberger, B., 2000b. Slabs in the lower mantle-results of dynamic modelling compared with tomographic images and the geoid. Phys. Earth Planet. Int. 118, 241-257.

- Steinberger, B., Antretter, M., 2006. Conduit diameter and buoyant hot rising speed of mantle plumes: implications for the motion of hot spots and shape of plume conduits. Geochem. Geophys. Geosyst. 7, Q11018.
- Steinberger, B., Calderwood, A.R., 2006. Models of large-scale viscous flow in the Earths mantle with constraints from mineral physics and surface observations. Geophys. J. Int. 167, 1461–1481.
- Steinberger, B., Holme, R., 2008. Mantle flow models with core-mantle boundary constraints and chemical heterogeneities in the lowermost mantle. J. Geophys. Res., in press, doi:10.1029/2007JB005080.
- Steinberger, B., O'Connell, R.J., 1998. Advection of plumes in mantle flow: implications for hotspot motion, mantle viscosity and plume distribution. Geophys. J. Int. 132, 412–434, doi:10.1046/j.1365–246x.1998.00447.x.
- Steinberger, B., Sutherland, R., O'Connell, R.J., 2004. Prediction of Emperor-Hawaii seamount locations from a revised model of global plate motion and mantle flow. Nature 430, 167–173.
- Tarantola, A., 2005. Inverse Problem Theory and Methods for Model Parameter Estimation. Society for Industrial and Applied Mathematics, Philadelphia.
- Thorne, M.S., Garnero, E.J., Grand, S.P., 2004. Geographic correlation between hot spots and deep mantle lateral shear-wave gradients. Phys. Earth Planet. Int. 146, 47–63.
- Wessel, P., Smith, W.H.F., 1991. Free software helps map and display data. EOS Trans. AGU 72, 445–446.
- Wilson, J.T., 1973. Mantle plumes and plate motions. Tectonophysics 19, 149– 164.
- Zhong, S., 2006. Constraints on thermochemical convection of the mantle from plume heat flux, plume excess temperature and upper mantle temperature. J. Geophys. Res. 111, doi:10.1029/2005JB003972.