# Towards a Quantitative Interpretation of Global Seismic Tomography

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We review the success of seismic tomography in delineating spatial variations in the propagation speed of seismic waves on length scales from several hundreds to many thousands of kilometers. In most interpretations these wave speed variations are thought to reflect variations in temperature. Careful consideration of shear wave, bulk sound, and, most recently, density variations is, however, producing increasingly compelling evidence for chemical heterogeneity (that is, spatial variations in bulk major element composition) having a first-order effect on the lateral variations in mass density and elasticity of the mantle. This has profound consequences for our understanding of mantle dynamics and the thermochemical evolution of our planet. We argue that the quantitative integration of constraints from seismology, mineral physics, and geodynamics, which underlies the inference of thermochemical parameters, requires careful uncertainty analyses and should move away from emphasizing visually pleasing images and single, nonunique solutions.

## 1. INTRODUCTION

Knowledge of the present-day scale and nature of the solid-state convection in Earth's mantle is key to our understanding of plate tectonics—and the surface processes and hazards associated with it—and of Earth's thermochemical evolution over long periods of geological time. Indeed, whether or not mantle convection occurs in separate layers and whether or not compositionally distinct domains have survived anywhere in the convecting system have major implications for models of Earth's early geological history and subsequent development. Many integrated views on mantle dynamics and chemistry have been proposed [e.g., *Hofmann*, 1997; *Kellogg et al*., 1999, *Helffrich and Wood*, 2001; *Albarède and van der Hilst*, 2002; *Anderson*, 2001, 2002], but firm evidence in support of any of the models is still lacking. Recently, significant progress has been made on a variety of research fronts, with seismological evidence having changed most dramatically.

Over the past two decades, global tomography, a class of inversion techniques for interpreting observations from earthquake records in terms of three-dimensional (3D) variations in Earth's elastic properties, has produced spectacular images of Earth's interior structure. Among the success stories of global tomography are the delineation of long-wavelength variations in elastic properties in Earth's mantle, which started in the early 1980s, and the detailed delineation, over the last decade or so, of trajectories of mantle convection [see reviews by, e.g., *Dziewonski and Woodhouse*, 1987; *Woodhouse and Dziewonski*, 1989;

Earth's Deep Mantle: Structure, Composition, and Evolution
Geophysical Monograph Series 160

10.1029/160GM05

*Masters*, 1989; *Romanowicz*, 1991; *Montagner*, 1994; *Masters and Shearer*, 1995; *Ritzwoller and Lavely*, 1995; *Dziewonski*, 1996; *Masters et al*., 2000; *Kárason and van der Hilst*, 2000; *Fukao et al*., 2001; *Romanowicz*, 2003]. It is encouraging to see that increasingly consistent information on the spatial patterns of wave speed variations is emerging from tomographic studies that use different data and/or techniques. The long-wavelength patterns are now fairly well established, and also on the issue of deep slabs there is growing consensus. Despite recent progress, however, the tomographic images of the return flow of mantle convection are still ambiguous, and there is no lack of controversy regarding the depth of origin, the morphology, the nature, and even the existence of so-called plumes.

One way of further improving spatial resolution and model accuracy is by data fusion, that is, the joint inversion of data that have different sensitivities to Earth's structure. Since these are often measured at different frequencies, it is becoming important to consider finite frequency effects, which is a topical subject of theoretical seismology [e.g., *Dahlen et al*., 2000; *De Hoop and van der Hilst*, 2005]. The biggest challenge is to be able to perform a complete waveform inversion; we are now able to calculate exact seismograms in a full 3D Earth, but the computational resources are still lacking to apply these exciting techniques to a realistic inverse problem [*Tromp et al*., 2005].

Although a major challenge in itself, the mere mapping of mantle structure at a wide spectrum of spatial scales is not the ultimate goal of seismic tomography. For seismology to be a key component of an inherently multidisciplinary effort aimed at understanding mantle dynamics, composition, and evolution, we must know the underlying physical or chemical causes of the variations in wave speed. Many computer simulations of mantle convection are based on instantaneous flow patterns calculated for purely thermal origins [e.g., *Schubert et al*., 2001] and imply simple scaling relationships between seismic wave speeds and density in tomographic models. However, in recent years it has become evident that not all inferred wave speed variations are consistent with a thermal origin and that significant regional variations in major element composition exist in Earth's mantle [e.g., *Ishii and Tromp*, 1999; *van der Hilst and Kárason*, 1999]. For example, it is increasingly likely that the so-called superplumes in the deep mantle beneath Africa [see also *Helmberger and Ni*, this volume] and the Pacific reflect changes in both temperature and composition [*Trampert et al*., 2004; see also *Samuel et al*., this volume]. The geochemical record on Earth's differentiation over geological time, the planetary heat budget, and the secular changes in formation and subsequent evolution (stabilization) of continents also suggest that compositional heterogeneity probably exists over a wide range of length scales [e.g., *Hofmann*, 1997; *Helffrich and Wood*, 2001; *Anderson*, 2002; *Albarède and van der Hilst*, 2002; see also the contributions to this volume by *Albarède*, *Anderson*, *Harrison and Ballentine*, *Righter*, and *Tackley*]. In concert with mineral physics and geodynamics, one frontier in seismological research thus concerns the detection and characterization of spatial variations in temperature and in mantle mineralogy and phase chemistry.

From existing mineral physics data, temperature and the iron and silicate content of the mantle appear to have the biggest influence on wave speeds [see also the contributions to this volume by *Badro et al*. and *Bukowinski and Akber-Knutson*], but information about *P*- and *S*-wave speeds alone is not enough to constrain these parameters. Indeed, it is important to have independent information on density variations, for instance, through analysis of gravity anomalies and quantitative integration of inferences from Earth's free oscillation frequencies. Knowledge on the nature of seismic anisotropy and attenuation would further constrain the thermochemical parameters, but their determination awaits major advances in seismic data analysis and theory.

A related challenge concerns model uncertainty. While much research effort has been put into increasing the resolution of the lateral and radial variations that can be imaged, relatively little progress has been made towards the quantitative assessment of the accuracy or uniqueness of the obtained models. Yet, this information is needed if we want to advance from a predominantly qualitative, semi-monodisciplinary to a more quantitative, multidisciplinary interpretation. Most published seismological models are solutions of an underdetermined inverse problem in the sense that the data are not sufficient to constrain independently all model parameters. In the best case, models of selected physical parameters represent an optimum fit to data, for instance, in the least-squares sense. But these fits are nonunique and often heavily influenced by a particular regularization (also referred to as damping). The same problems plague models based on mineral physics or geochemical data. The disciplinary solutions are likely to fall in different parts of the permissible model space, and one must consider uncertainty and error in order to find common ground (Plate 1).

The organization of this paper roughly follows the topics mentioned in the preceding paragraphs, and we will end with a discussion of outstanding issues and future challenges.

## 2. MANTLE STRUCTURE INFERRED FROM SEISMIC TOMOGRAPHY

Since the advent of seismic tomography in the late 1970s, global tomographic imaging has evolved along complementary lines, leading to the so-called high-resolution models and long-wavelength models[1]. This has several reasons. Owing to theoretical and practical considerations, seismic imaging applications have long involved relatively small subsets of the available data. On the one hand, solving the equation of motion in its most general form is not yet possible for large-scale problems, and several theoretical approximations need to be made in order to obtain tractable formulations. On the other hand, high natural noise levels in certain frequency bands and the band limitations due to instrument filters and source characteristics yield specific frequency bands for seismic analysis. Furthermore, different types of waves are sensitive to different elastic properties. And, finally, different parameterizations have been used to achieve different objectives. A seismologist thus faces a choice as to which data and, along with it, which theoretical approximations and model parameterizations, to use for a specific application.

High-resolution and long-wavelength models can have a very different appearance, but it is useful to see them as complementary rather than competing depictions of Earth's structure. Tests have shown that in regions of adequate data coverage the high-frequency body wave arrivals map long-wavelength structure correctly [e.g., Figure 2 in *van der Hilst et al.*, 1997], and with a careful spectral analysis the long-wavelength models will give a representation unbiased by small-scale structures, such as slabs in the upper mantle [*Trampert and Snieder*, 1996]. With growing data sets, the development of more powerful inversion and wave propagation theories, and increasing computational abilities, these approaches will continue to converge.

We deliberately omit discussing anisotropic and attenuation tomography. It is well established that the Earth presents distinct anisotropic regions [e.g., *Montagner*, 1998], but to date little consensus has been reached on details in existing models, except maybe in the shallowest mantle. On the interpretational side, numerous experimental data exist for anisotropic minerals, but relating observed seismic anisotropy to the chemistry of the mantle relies on many assumptions that currently cannot be unambiguously tested. Attenuation is also clearly present in the mantle [e.g., *Romanowicz and Durek*, 2000], but models strongly vary from author to author due to unresolved theoretical issues (e.g., scattering and focusing vs. intrinsic attenuation). Understanding activation processes for lower-mantle attenuation and obtaining experimental data still remain formidable challenges which make the interpretation of attenuation tomography even more speculative than that of anisotropic tomography.

[1] Despite popular use, references to high- vs. low-resolution models can be misleading or even incorrect. The model parameters underlying the "long-wavelength" models (i.e., the spherical harmonic coefficients) may actually be resolved better than the parameters (e.g., wave speed at nodes or in small cells) representing "high-resolution" models. In the context of this discussion, high-resolution merely indicates that—potentially—contrasts in elastic properties can be detected over smaller spatial length scales.

### *2.1. Long-Wavelength Models*

Long-wavelength (i.e., thousands of km) variations in wave propagation speeds have been inferred from a combination of broadband waveforms, long-period body wave arrival times, surface wave dispersion data, and splitting functions of Earth's free oscillations [e.g., *Su et al.*, 1994; *Masters et al.*, 1996, 2000; *Mégnin and Romanowicz*, 2000; *Gu et al.*, 2001; *Ritsema et al.*, 1999; *Ekström and Dziewonski*, 1998; *Li and Romanowicz*, 1996; to name but a few]. Because a combination of body- and surface waves and mode data can be used, the constraints on *S*-wave models are often better than in the case of the high resolution *P*-wave models (see below). The images are typically represented horizontally by global basis functions (surface spherical harmonics). This important class of models has continued to improve over the past two decades [e.g., *Romanowicz*, 2003], but many challenges remain. In the midmantle, substantial differences still exist between results of different research groups, in particular when different data sets are used [e.g., *Becker and Boschi*, 2002], and the magnitude of the wave speed perturbations is quite uncertain.

In the uppermost mantle, the credibility of the models has been established both by their ability to match independent waveform data and by their correlation with tectonic features. *Trampert and Woodhouse* [2000] tested all recent long-wavelength fundamental mode phase velocity models against independent waveform data and found a reassuring agreement between them. In a test against independent splitting functions, *Ritzwoller and Lavely* [1995] showed that a robust pattern of the Earth's mantle emerged at the lowest degrees, even if different data and different mapping strategies were employed. Although this quantitative comparison is now almost 10 years old, more recent long-wavelength models correlate highly with the models in the *Ritzwoller and Lavely* study.

Although smaller-scale structures can now be imaged with greater confidence, the overall view that emerged from the pioneering studies by *Masters et al*. [1982], *Woodhouse and Dziewonski* [1984], and *Dziewonski* [1984] has proved fairly robust. In the uppermost mantle, these early studies delineated the low wave speeds associated with midoceanic ridges and regions of the western Pacific characterized by back-arc volcanism (Plate 2) and demonstrated that the structure beneath continents differs from the oceanic mantle to several hundred km depth (with Precambrian cratons, shields, and platforms marked by fast seismic wave propagation to depths of 200 km and larger in some continental regions). Heterogeneity in the upper-mantle transition zone (between the seismic discontinuities near 410- and 660-km depth) and near the base of the mantle is manifest at very long wavelengths (Plate 2), with a predominance of fast wave propagation in the mantle beneath the circum-Pacific "Ring of Fire" and slow speeds beneath Africa and the central Pacific. This structure explains the long-wavelength variations in the gravity field [*Richards and Hager*, 1984; *Hager et al*., 1985; *Cazenave et al*., 1989] and correlates well with sites of post-Mesozoic subduction (recycling) of oceanic lithosphere [*Richards and Engebretson*, 1992; *Ricard et al*., 1993]. The shallow and lowermost mantles are marked by relatively strong heterogeneity, but the inferred magnitude of elastic heterogeneity decreases away from these boundary regions. In the midmantle, recent models show a low-amplitude white spectrum [*Romanowicz*, 2003], but it is here that models differ most.

### *2.2. High-Resolution Models*

In a largely separate effort, large amounts of travel time data and local basis functions (cell or grid parameterizations with a spacing of the order of 1–4°) have been used to delineate Earth's structure on a finer scale, both with *P*-data [e.g., *Fukao et al*., 1992; *van der Hilst et al*., 1997; *Vasco and Johnsen*, 1998; *Bijwaard et al*., 1998; *Kennett et al*., 1998; *Boschi and Dziewonski*, 2000; *Kárason and van der Hilst*, 2001; *Montelli et al*., 2004] and with *S*-data [e.g., *Grand*, 1994; *Grand et al*., 1997; *Widiyantoro et al*., 1998]. In the *P*-wave studies, data coverage is generally not as good as in long-wavelength shear wave tomography. The uneven distribution of earthquakes and stations and the fact that surface waves provide relatively weak constraints on compressional wave speed means that high resolution is mainly restricted to seismically active regions, such as plate boundaries, or continental regions with many seismograph stations, whereas large areas beneath oceans remain without effective sampling. In modern applications, the uneven data coverage is partly balanced by the use of adaptive grids [*Abers and Roecker*, 1991; *Fukao et al*., 1992; *Widiyantoro and van der Hilst*, 1996; *Sambridge and Gudmundson*, 1998; *Bijwaard et al*., 1998; *Kárason and van der Hilst*, 2001; *Montelli et al*., 2004] and, in part, remedied by the use of different data types along with 3D sensitivity kernels to account for frequency differences [e.g., *Dahlen et al*., 2000; *Kárason and van der Hilst*, 2001; *Montelli et al*., 2004; *van der Hilst et al*., in preparation].

The largest single data source for this class of imaging is the *Bulletin of the International Seismological Centre*. These data are rather noisy, but the reprocessing by *Engdahl et al*. [1998] has produced a data set of high quality and research potential. In recent years, individual efforts have been producing large data sets of travel time measurements from digital waveforms (e.g., by waveform cross-correlation [*Masters et al*., 1996; *Ritsema et al*., 1999]). Before too long these compilations can be expected to become the data set of choice for this class of tomographic imaging because they contain a larger proportion of later arrivals. As a next step, computational techniques are being developed that enable the use of complete seismograms [*Tromp et al*., 2005].

Image reliability is often assessed (rather qualitatively) by model comparison and with so-called checkerboard tests, where the ability to recover a known input model is determined and used as a proxy for image reliability. Many studies have now established that the models do not critically depend on the choice of parameterization and inversion technique [e.g., *Spakman and Nolet*, 1988; *Boschi and Dziewonski*, 1999], but uneven data coverage and inconsistent data quality remain important issues.

By producing increasingly detailed images of slabs of subducted lithosphere, the most tangible trajectories of mantle flow, this class of tomographic model has made crucial contributions to the debate of layered vs. whole mantle convection, which has divided Earth scientists for almost a half century [see, e.g., recent reviews by *Hofmann*, 1997; *Helffrich and Wood*, 2001; *Albarède and van der Hilst*, 2002; *Anderson*, 2001, 2002; *Tackley*, 2002]. First on a regional [e.g., *Spakman et al*., 1988; *van der Hilst et al*., 1991] and later on the global scale [e.g., *van der Hilst et al*., 1997] it was shown that slabs can penetrate across the 660-km discontinuity, implying substantial mass exchange between the upper and lower mantle. The excellent agreement between *P* and *S* images [*van der Hilst et al*., 1997; *Grand et al*., 1997], at least to ~1900-km depth, and the increasing similarity between slablike features in high-resolution and long-wavelength models [e.g., *Fukao et al*., 2001; *Romanowicz*, 2003] lends further credibility to these deep structures.

But the issue is still far from being solved. Structural complexity of slab trajectories, with some slabs deflecting and apparently stagnating in the upper mantle transition zone and others penetrating to larger depths (Plate 3), demonstrates that neither strict layering at 660 km nor whole-mantle mixing with unobstructed slab penetration is a realistic flow model [*van der Hilst et al*., 1991, 1997; *Fukao et al*., 1992, 2001]. Combined with the emerging seismological evidence for compositional heterogeneity (see also next section)—as well as the inferences from geochemistry and Earth's heat budget—this observation inspired some of us [*van der Hilst and Kárason*, 1999; *Kellogg et al*., 1999; *Albarède and van der Hilst*, 2002] to explore other scenarios of (thermochemical) mantle convection and evolution.

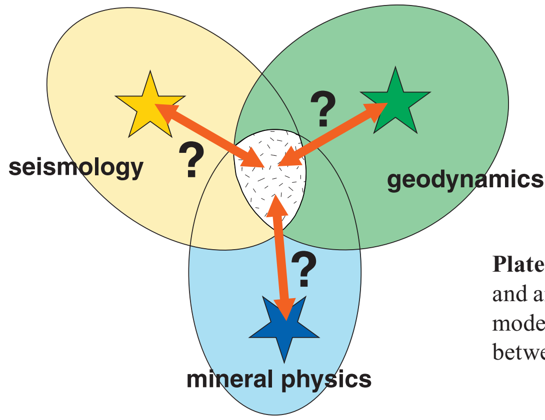


**Plate 1.** Optimal fits to incomplete data sets (depicted by stars) often depend on the type and amount of regularization of the inverse problem and are not unique. Unless all likely models (depicted by the ellipses) are explored and uncertainty accounted for, an overlap between models from different data sets is difficult to find, let along quantify.

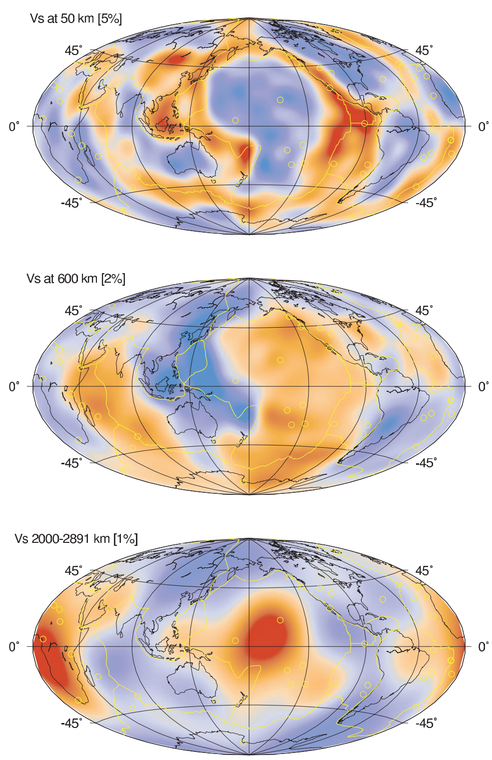


**Plate 2.** Models at 50- and 600-km depth obtained from the inversion of our fundamental and higher-mode surface wave phase velocity maps for variations in shear wave speed at a particular depth. The lowermost mantle layer is the most likely model from *Trampert et al*. [2004]. The perturbations are shown in percent variations with respect to PREM [*Dziewonski and Anderson*, 1981]. Negative wave speed anomalies are depicted by red colors and positive anomalies are in blue. The maximum scale is indicated beside each plot. The yellow lines indicate plate boundaries; yellow circles indicate hotspots.

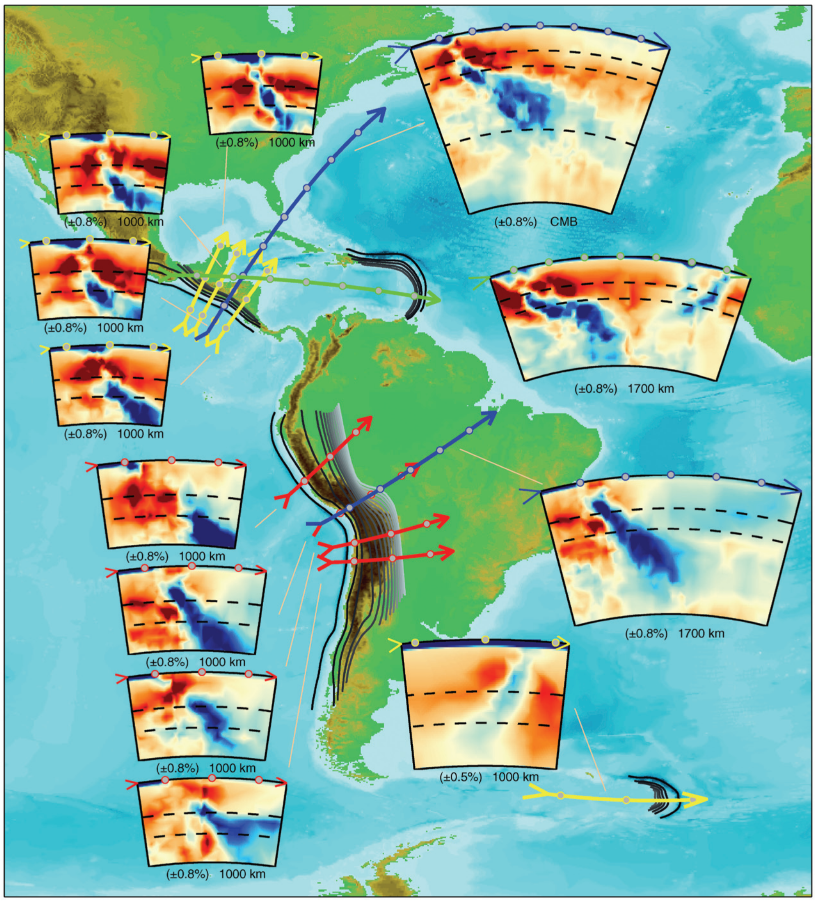


**Plate 3.** Cross-sections of a recent *P*-wave model [*van der Hilst et al*., in preparation] to illustrate the likely complexity of slab structures. This model was obtained by inversion of travel time data from *P*, *PP*, *pP*, and several core phases (*PKP*, *Pdiff*), using an irregular grid parameterization, finite frequency sensitivity kernels [see also *Kárason and van der Hilst*, 2000], and corrections for crustal structure according to CRUST2.0 [http://mahi.ucsd.edu/Gabi/crust2.html]. The perturbations are shown in percent with respect to ak135 [*Kennet et al*., 1995]. Negative anomalies are depicted by red colors and positive anomalies are in blue. The maximum scale is indicated below each cross-section together with its maximum depth. CMB, core–mantle boundary.

For technical reasons, plumes are far more difficult to image and are currently hotly debated among scientists. Recently, *Montelli et al*. [2004] described intriguing images of plumes, but further research is required to establish conclusively the existence, nature, origin depth, and volume of mantle upwellings. We speculate that over the next 5 years, improvements in theory and data coverage, especially from ocean bottom seismic experiments, will lead to significant progress on this crucial feature of mantle flow.

## 3. ORIGIN OF WAVE SPEED ANOMALIES: DEMISE OF THE THERMAL PARADIGM

Beyond giving insight into the present-day pattern of mantle flow, one would like to use tomographic models as input, or boundary condition, for geodynamical simulations of mantle flow. This is not trivial, however. Seismic tomography yields 3D wave speed variations, whereas convective flow is driven by lateral variations in buoyancy, i.e., mass density. It has been known since *Birch* [1961] that there are systematic relationships between *P*-wave speed and density in crustal rocks, and it thus seemed sensible to assume scaling relations between seismic wave speed and mass density for material in the deep Earth. If one makes the assumption that temperature variations within the convecting mantle are responsible for variations in seismic speed and density, results from mineral physics experiments [e.g., *Anderson et al*., 1984] can be used to establish that deep mantle shear velocity and density are highly correlated with a ratio $\delta\ln\rho/\delta\ln V_s \approx 0.4$. This concept was used in pioneering studies in the mid-1980s. Soon after the construction of the first tomographic whole-mantle models [*Woodhouse and Dziewonski*, 1984; *Dziewonski*, 1984] it was recognized that the geoid was negatively correlated to the variations in wave speed. *Hager et al*. [1985] used lower-mantle density perturbations obtained from wave speed variations by simple scaling relationships to drive viscous flow and to generate dynamically maintained topography at the core–mantle boundary and the Earth's surface. The total gravity field due to the inferred density variations and the flow-induced topography explained the long-wavelength geoid remarkably well. The success of these and later studies led to the widespread view that mantle convection is controlled by thermal processes.

Using the growing mineral physics data base, one can test whether such a thermal interpretation of the available tomographic models is warranted. Laboratory experiments at deep mantle conditions show that heating (cooling) material reduces (increases) simultaneously the shear and bulk modulus and density of candidate minerals [e.g., *Anderson*, 1995]. The consequence of a purely thermal origin, therefore, is that bulk sound speed, shear wave speed, and density should be perfectly correlated to one another at all depths. But this strong positive correlation appears to hold only in some parts of the Earth's mantle.

Tomographically inferred isotropic wave speed variations in the shallow mantle ($z < 200$ km) correlate well with tectonic features and expectations for the associated temperature field (Plate 2, top). Midoceanic ridges, known to be hotter than average, are seismically slower than average; the cooling of the oceanic lithosphere with age appears as progressively faster wave speeds away from the midoceanic ridge systems; and ancient continental shields are in general marked by low average heat flow and faster than average seismic propagation speed. This is consistent with analyses of mineral physics data, which show that at shallow depths in the mantle, seismic velocities are generally much less sensitive to composition than to variations in temperature [*Deschamps et al*., 2002; *Cammarano et al*., 2003]. However, chemical depletion of subcontinental lithosphere [e.g., the tectosphere hypothesis of *Jordan*, 1975] can lead to small detectable changes in wave speeds identifiable by considering decorrelations between *P*- and *S*-wave tomography [*Goes et al*., 2000], combined tomography and gravity data [*Forte and Perry*, 2000; *Deschamps et al*., 2002; *van Gerven et al*., 2004] and seismic anisotropy [*Beghein and Trampert*, 2004].

While tomographic images are a reasonable proxy for the temperature field in the shallowest mantle, this relationship becomes increasingly more tenuous as we go deeper in the mantle. With increasing pressure the temperature sensitivity of velocities decreases and seismic wave speeds become more sensitive to composition [*Anderson*, 1989; *Trampert et al*., 2001]. If wave speeds and mass density are not dominated by temperature effects, then it is not necessarily meaningful to assume a constant scaling between $\delta\ln\rho$ and $\delta\ln V_s$. Recent interpretations of gravity anomalies and Earth's free oscillation data [*Ishii and Tromp*, 1999, 2001, 2004] clearly show low-to-negative correlations between $\delta\ln\rho$ and $\delta\ln V_s$ in the deep mantle. Using a full-model space search technique, *Resovsky and Trampert* [2003] confirmed that the low-to-negative correlations are, indeed, highly probable, given existing seismic data throughout the mantle. While they may be consistent with geodynamic observables [e.g., *Forte and Mitrovica*, 2001], mass density anomalies derived by direct scaling of shear wave speed variations do not explain the spectral properties of the of Earth's free oscillation. Similarly, throughout the mantle, clear observations of low-to-negative correlations between $\delta\ln V_s$ and $\delta\ln V_\phi$ [2] have been made [*Masters et al*., 2000; *Saltzer et al*., 2001; *Resovsky and Trampert*, 2003]. This is irrefutable observational proof that temperature alone

[2] In an isotropic medium the bulk sound speed $V_\phi$ can be derived from the P - and S-wave speed. With $V_p = \sqrt{(\kappa + 4/3\mu)/\rho}$, and $V_s = \sqrt{\mu/\rho}$, then $V_\phi = \sqrt{V_p^2 - 4/3V_s^2} = \sqrt{\kappa/\rho}$.

cannot be responsible for wave speed and density anomalies. As a consequence, the paradigm of purely thermally driven mantle flow is in need of revision, as already suggested by *Anderson* [2001], using different arguments.

## 4. SEISMOLOGICAL EVIDENCE FOR COMPOSITIONAL HETEROGENEITY

The anomalous frequencies of Earth's free oscillations are not the only seismological observations suggesting lateral variations in bulk composition in Earth's mantle. Other lines of evidence for compositional heterogeneity include discrepancies between the seismologically inferred and theoretically predicted ratio between relative changes in shear and compressional wave speed, the conspicuous anticorrelations between shear- and bulk sound speed, and the anomalously large range of the Poisson's ratio beneath some geographical regions. Collectively, this evidence has begun to suggest that variations in composition occur over a wide range of length scales, from local (several 100s of km) to global (e.g., the spherical harmonic degree 2 pattern).

### *4.1. Radial and Lateral Variation of* $R = \delta\ln V_s/\delta\ln V_p$

In the seismologic and mineral physics communities, the depth dependence of the spherical average of the ratio $R = \delta\ln V_s/\delta\ln V_p$ has received considerable attention in the past 5 years or so. In combination with mineral physics data, the seismologically measured ratio is thought to indicate whether thermal and/or chemical causes are responsible for the observed lateral variations in wave speeds [*Karato and Karki*, 2001]. However, there are several caveats that one should be aware of. First, in any study based on a comparison between *P* and *S* speed, one should make sure that the sampling by *P*- and *S*-sensitive data is geographically similar [*Robertson and Woodhouse*, 1996; *Kennett et al*., 1998; *Saltzer et al*., 2001, 2004]. Second, there are several ways of determining *R*, and the result is not always the same [see, e.g., *Masters et al*., 2000; *Saltzer et al*., 2001, 2004]. Furthermore, the diagnostic value of *R* is often overstated. Scientists concur that large values of *R* (i.e., larger than 2.5) cannot be due to a purely thermal origin; contrary to common perception, however, the reverse is not true: While consistent with a thermal origin, small values cannot rule our compositional effects. Indeed, several seismological studies, either with travel time or normal mode data, have revealed substantial wave speed anticorrelations (suggesting nonthermal effects) in mantle regions where *R* values remain close to or far below values predicted from a purely thermal origin [*Beghein et al*., 2001; *Saltzer et al*., 2001]. Far-reaching conclusions based on the *R* value alone should, thus, be considered with a healthy dose of caution and skepticism.

It is generally agreed that *R* increases with depth, particularly close to the core [*Masters et al*., 2000], but focusing on the radial dependence is a misleading oversimplification since lateral variations of *R* can be significant and important [*Masters et al*., 2000; *Saltzer et al*., 2001]. *Saltzer et al*. [2001] found that the strongest increase of *R* with depth occurs away from post-Mesozoic subduction regions, suggesting that the high values most diagnostic of compositional differences occur in the same regions where the shear wave speed is lowest, that is, in the deep mantle beneath southern Africa and the central and western Pacific. *Deschamps and Trampert* [2003] showed that the width of histograms of lateral variations of *R* give an unambiguous indication of the presence of chemical heterogeneities in the lowermost mantle, but that by itself the value of *R* can never give quantitative information on the magnitude of temperature and composition due to an invariance to arbitrary scaling.

### *4.2. Long-Wavelength Anticorrelations of Wave Speeds and Density*

Tomographic inversion of *P*- and *S*-data reveals a strong correlation ($r \approx 0.8$) between *P*- and *S*-wave speed anomalies at all depths in the mantle [*Kennett et al*., 1998; *Ishii and Tromp*, 1999; *Masters et al*., 2000; *Saltzer et al*., 2001; *Resovsky and Trampert*, 2003], although some models reveal a gradual decline in correlation beyond 2000-km depth [*Saltzer et al*., 2004]. The high correlation is primarily due to the fact that the propagation speeds of compressional and shear waves are both dominated by changes in shear modulus or density [e.g., *Su and Dziewonski*, 1997; *Kennett et al*., 1998; see also *Ricard et al*., this volume]. In the deep mantle the effect of the bulk modulus (incompressibility) on *P*-wave speed is small and reaches a minimum near 2000-km depth [*Kennett et al*., 1998]. While results vary [*Masters et al*., 2000], simultaneous inversions for shear wave and bulk sound speed all reveal small or negative correlations between variations in bulk sound and shear wave speed in the deep mantle [*Su and Dziewonski*, 1997; *Kennett et al*., 1998; *Ishii and Tromp*, 1999; *Masters et al*., 2000]. We note that the differences between the models are most likely due to different regularizations of the inverse problem. Using a full-model space search, *Resovsky and Trampert* [2003] found that all published correlations were compatible with the available data and that negative correlations are robust (Figure 1).

Density has a different sensitivity to compositional changes than to bulk sound and shear wave speeds. *Ishii and Tromp* [1999] were the first to identify small or negative correlations between density and shear sound speed in the lower mantle. Their model was criticized as not being robust with respect to damping [*Resovsky and Ritzwoller*, 1999; *Romanowicz*,

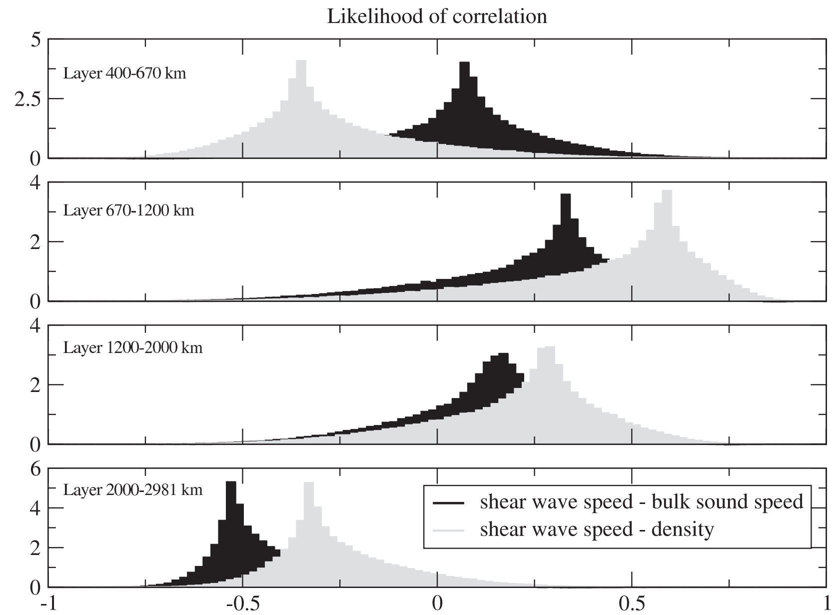


**Figure 1.** Likelihoods of correlations generated by randomly sampling the probability density functions for $\delta \ln V_s$, $\delta \ln V_\phi$, and $\delta \ln \rho$, after *Resovsky and Trampert* [2003]. The uppermost mantle layer is omitted because the low spherical harmonic degree expansion used does not capture the more complicated nature of Earth's structure near the surface.

2001] and initial models and parameterization [*Kuo and Romanowicz*, 2002]. While this may be true for the amplitude of the inferred density anomalies, the pattern and sign of the anomalies proved to be correct. *Resovsky and Trampert* [2003] identified all models compatible with normal mode splitting functions and fundamental mode and overtone phase velocity data. Their approach is based on forward modeling and does not require regularization; consequently, the correct amplitude can be found even in the presence of parameters with largely varying sensitivities. They confirmed that negative correlations between density and shear sound speed variations are most likely in the lowermost mantle and transition zone (Figure 1).

The amplitude of the density signal also provides compelling evidence for the presence of chemical heterogeneity. At and beyond transition zone depths, the amplitude of density anomalies are likely to be at least as large as that of shear sound speed variations [*Resovsky and Trampert*, 2003]. Existing mineral physics data show that this is not compatible with a purely thermal origin [e.g., *Karato and Karki*, 2001].

### *4.3. Evidence for Compositional Heterogeneity on Shorter-Length Scales*

The results from the analyses of $R = \delta \ln V_s / \delta \ln V_p$, and the wave speeds and density anticorrelations mentioned in the preceding sections, all imply that variations in bulk composition deep in Earth's mantle can occur on scale lengths in excess of tens of thousands of km. Indeed, the inferred compositional heterogeneity is qualitatively consistent with the convection model proposed by *Kellogg et al.* [1999], in that the most anomalous deep mantle regions would be located away from the subducting slabs, in regions characterized by the lowest shear wave speeds. However, regional studies have begun to reveal lateral variations in composition on a much smaller length scale as well. *Saltzer et al.* [2004] inverted some 15,000 relative *P* and *S* times, obtained by broadband waveform cross-correlation, for variations in $V_p$, $V_s$, and $V_\phi$ beneath a great circle arc from source regions in the northwest Pacific to receivers in North America. In the deep mantle beneath Alaska, they detected regions of low- and anti-correlations between $V_s$ and $V_\phi$ as small as 500 km (Plate 4). The anticorrelation and the associated large range in inferred Poisson's ratios cannot be explained by currently available data from mineral physics, and *Saltzer et al.* [2004] thus proposed that a combination of thermal and compositional changes is needed to explain the observations. Interestingly, the inferred range of variation in temperature, iron, and silicate perovskite is in excellent agreement with inferences from normal modes, which are sensitive to much longer-length scales. In combination, the normal mode and body wave studies suggest that lateral variations in bulk composition can occur over a wide range of length scales, but that a careful analysis is required to detect such heterogeneity. Knowing the scaling characteristics of compositional heterogeneity is important for understanding mantle-mixing over long periods of geological time [e.g., *Albarède*, this volume].

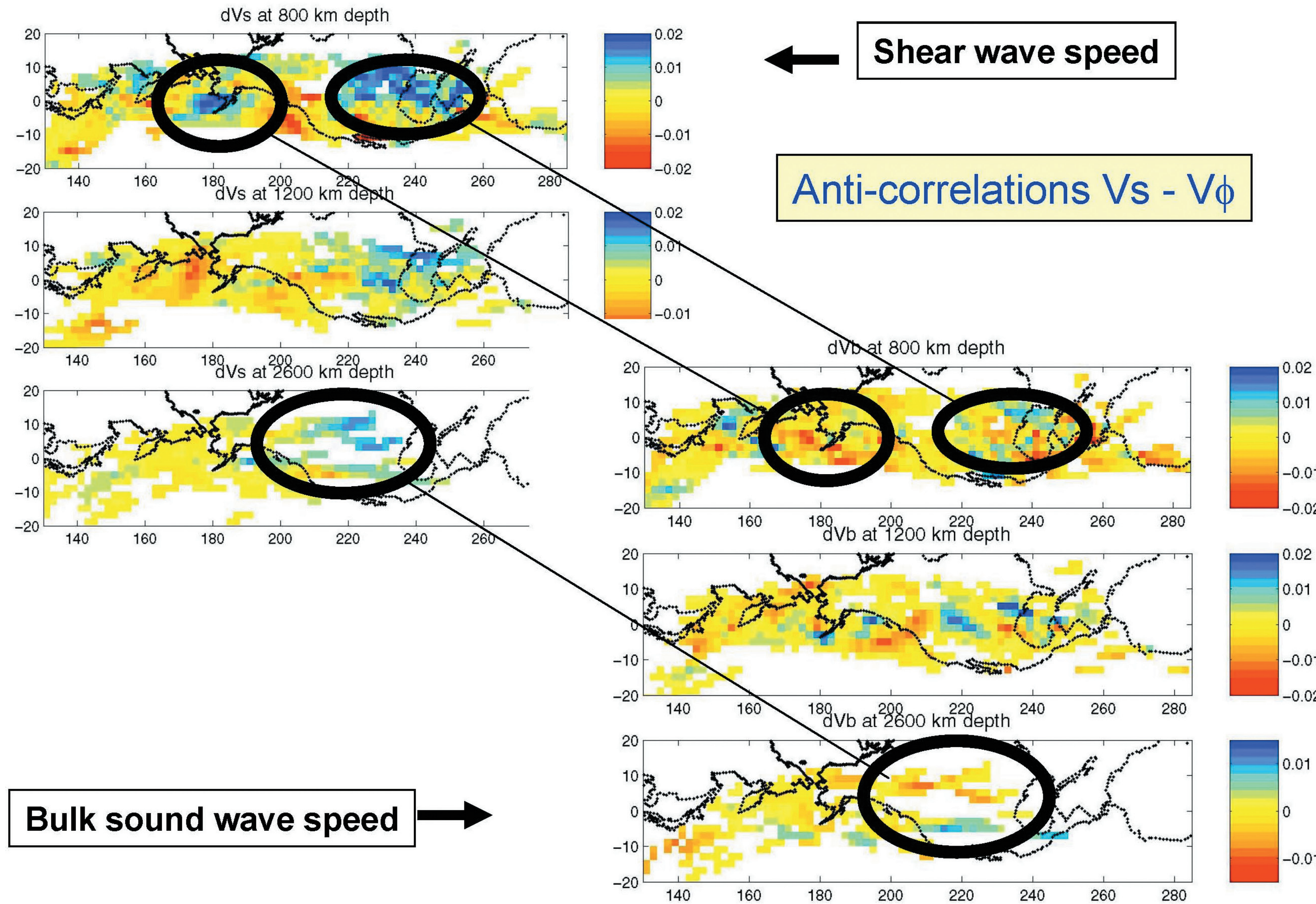


**Plate 4.** *S*-wave and bulk sound speeds in the deep mantle beneath Alaska and the north Pacific, after *Saltzer et al.* [2004]. Highlighted are some clear anticorrelations for well-resolved areas of the model. Such anticorrelations are resolved at length scales of several hundred kilometers and larger. Smaller-scale variations cannot be resolved with the data and technique used.

## 5. QUANTITATIVE INTERPRETATION OF TOMOGRAPHIC AND MINERAL PHYSICS DATA

For several reasons it has remained difficult to provide a quantitative interpretation of tomographic models or their related parameters described in the previous section (that is, the ratio $R$ of the relative variation in shear and compressional wave speed, the Poisson's ratio, or the correlation—or lack thereof—between wave speeds) in terms of temperature and composition. On the one hand, we recognize outstanding issues for seismology. Constraining density variations in Earth's interior, a key ingredient for geodynamical studies, is still a formidable challenge (so far only the lowest even-numbered spherical harmonic degrees have been constrained). Furthermore, the uneven seismic source and receiver distribution produce substantial spatial variations in the reliability of the estimates of $V_s$, $V_p$, and $V_\phi$ and, to make matters worse, the uncertainties are different for each wave type because of differences in sampling and concomitant effects of regularization. On the other hand, we recognize outstanding issues for mineral physics research. Constraints from experimental and theoretical mineral physics exist for only some minerals and often depend critically on extrapolations over large pressure and temperature ranges and from single crystal measurements to the behavior of rock aggregates. Furthermore, experimental and ab initio results do not always agree. Moreover, the effects of, for instance, oxidation state, minor elements, and impurities on mineralogy, transport properties (such as viscosity and thermal and electric conductivity), element partitioning, and elasticity are not well known [*e.g., Badro et al*., 2005; McCammon, this volume].

### *5.1. Uncertainty Analysis and Model Space Searches*

Even if we do not know the origin and magnitude of all uncertainties, we must try to estimate the known uncertainties and use them in quantitative joint interpretations of seismological and mineral physics data. *Forte and Mitrovica* [2001] were the first to quantify variations in (what they called) effective temperature and composition, using tomographic models of relative bulk and shear sound variations. However, *Deschamps and Trampert* [2003] showed that realistic uncertainties in the conversion factors and in the tomographic models yielded a large uncertainty in the inferred temperature field (50%, in their study) and left composition largely unconstrained.

A major problem with the use of selected tomographic models as input data for such studies is the imprint of regularization on the solution. Tomographic problems are both overdetermined, in the sense that there are typically more data than model parameters, and underdetermined, in the sense that not all model parameters can be resolved independently. Moreover, real data are noisy. As a consequence, the generic tomographic inversion problem does not have a unique solution. Many realizations of model parameters can produce acceptable fits to the data, and typically the seismologist forces a unique solution by imposing sensible—but subjective—constraints on the solution. One should realize that in such a case, the tomographic solution in mantle regions that are not effectively sampled by the seismic waves is entirely controlled by the combination of a priori assumptions and ad hoc regularization. Worse, even in regions that are well sampled, regularization may severely degrade the parameter estimation. If the aim is merely to produce a visually appealing image, that is, if only the geographic pattern of wave speed variations is of interest, than this may not be a serious problem. But the models produced this way (the stars in the cartoon of Plate 1) may, in fact, be sufficiently far away from the real Earth (depicted as the checkered field) to invalidate quantitative interpretations or model comparisons.

The problems associated with the use of a single model, and the bias and error due to regularization, can be avoided with techniques that explore the entire model space. Several studies have shown that the statistical properties of distributions of a large family of acceptable solutions contain different and often more meaningful information than does a single solution [*Mosegaard and Tarantola*, 1995; *Sambridge and Mosegaard*, 2002; *Beghein et al*., 2002; *Shapiro and Ritzwoller*, 2002; *Resovsky and Trampert*, 2003; *Trampert et al*., 2004].

### *5.2. Sensitivities of Wave Speeds to Temperature and Composition*

Sensitivities of wave speeds to temperature and composition as a function of depth can be calculated using mineral physics data and equation of state (EOS) modeling. Many EOS models have been proposed and used for Earth studies [*Anderson*, 1989; *Poirier*, 1991; *Stacey*, 1992; *Anderson*, 1995]. The approaches that are most commonly used are either based on third-order finite strain theories or on a Mie–Grüneisen description. *Jackson* [1998] concluded that third-order Eulerian finite strain isotherms and isentropes are adequate for the range of strains encountered in the lower mantle and further showed that hot finite strain isentropes are consistent with the Mie–Grüneisen–Debye description of thermal pressure and a cold isothermal third-order compression. If we then fix a reference temperature and composition for the lower mantle using a 1D seismic reference model and choose the right mineral physics data, it is straightforward to obtain the sensitivities analytically or numerically [*Karato*, 1993; *Trampert et al*., 2001; *Stacey and Davis*, 2004].

In reality it is not that simple. We don't really know the thermochemical reference state of the Earth [see *Williams and*

*Knittle*, this volume], and many different combinations of temperature and composition are compatible with a chosen seismic reference model [*Anderson*, 1989; *Stixrude et al*., 1992; *Jackson*, 1998; *Deschamps and Trampert*, 2004]. Furthermore, both experimental and ab initio mineral physics data contain uncertainties, and there appears to be an inconsistency in the shear modulus of magnesium perovskite between experimental and ab initio data [*Deschamps and Trampert*, 2004]. In the same spirit as the model space searches mentioned above, instead of selecting one particular data set (or reference state), one can vary all parameters within their reasonable or measured bounds to obtain insight into uncertainties in the sensitivities. Such an exercise reveals that uncertainties in mineral physics data and reference state are equally important [*Trampert et al*., 2001]. While a particular choice of mineral physics data strongly influences the inferred reference state, it has only little effect on the derivatives themselves [*Deschamps and Trampert*, 2004; *Trampert et al*., 2004]. The importance of considering the full family of derivatives is illustrated by the fact that most published temperature derivatives fall within two standard deviations of our preferred mean derivatives [*Trampert et al*., 2004], implying that there is no formal disagreement between any of them. Noticeable differences in tomographic interpretations arise only when considering a single realization from the wide range of plausible solutions.

### *5.3. Importance of Mass Density*

The influence of aluminum on elastic properties is not yet well known [*Yagi et al*., 2004], but the effect of calcium is probably small [*Shim et al*., 2000; *Deschamps and Trampert*, 2003]. With a caveat concerning aluminum, it is thus reasonable to assume that most of the 3D structure seen by seismic data is due to spatial variations in iron, silicon (through a perovskite and magnesiowüstite ratio), and temperature. Even if we had accurate estimates of shear- and bulk sound speed variations at every point in the mantle, we would only have two constraints for these three unknowns. *Forte and Mitrovica* [2001] reduced by one the number of unknowns by inverting for an effective temperature (combination of real temperature and iron) and effective composition (combination of perovskite and iron). They showed that the effective temperature correlates highly with shear wave speed variations and argued that it is a good proxy for temperature. Realizing that knowledge of density variations would allow to distinguish between perovskite and iron effects, *Forte and Mitrovica* [2001] assumed that variations in density and shear wave speed are perfectly correlated, with a ratio between 0.1 and 0.3. This assumption is questionable, however, since several studies have now shown beyond reasonable doubt that density variations are not correlated with shear speed variations (see discussion above). Independent constraints on density thus prove crucial to infer correct temperature and compositional variations.

### *5.4. Probabilistic Tomography*

Probabilistic tomography can be used for the construction and, in particular, evaluation of long-wavelength models [*Beghein et al*., 2002; *Resovsky and Trampert*, 2002, 2003]. The advantage of the approach is that all models compatible with the data are considered. The family of admissible solutions is converted into likelihoods for wave speeds and density, which can thus be regarded as a compact representation of the seismological data. The likelihoods can subsequently be narrowed by independent data, such as gravity measurements [*Resovsky and Trampert*, 2003].

Full-model space searches are very computer-intensive since the space to be explored grows exponentially with the number of unknowns. So far we have managed to search only model spaces containing up to 30 parameters. This requires a careful model parameterization. In global applications, the approach is currently useful only where data and model parameters can be expanded in spherical harmonics. Each spherical harmonic coefficient can be inverted for up to 30 depth parameters by using a separate processor. Although limiting in terms of lateral and vertical resolution, the restriction in the number of parameters does not lead to biases. Indeed, we found [*Beghein and Trampert*, 2004] that a family of models for a thick layer represents the correct statistical average of the families for finer layers. This is because all models compatible with the data are considered and the probability density functions are thus nothing more than a compact representation of the data. Caution is necessary only in the discussion of geodynamic consequences. Combined with probability density functions for sensitivities from mineral physics, the probability density functions for seismological heterogeneities can be converted into likelihoods for variations of temperature and composition in the lower mantle (Plates 5–7) [*Trampert et al*., 2004].

For a detailed description of the concept we refer to recent papers by Trampert and co-workers. Here we summarize some of the key results that have been obtained so far. At the longest wavelengths (even degrees only): (i) The availability of an independent density constraint is essential for producing robust maps of temperature and composition; (ii) shear wave speed variations do not reflect temperature variations alone and thus should not be used to infer thermal buoyancy; (iii) throughout the mantle, significant chemical variations are required to explain seismological observations with the currently available mineral physics data. Iron variations are strongest in the lowermost mantle, but silicate variations appear equally strong throughout the lower mantle; (iv) density and

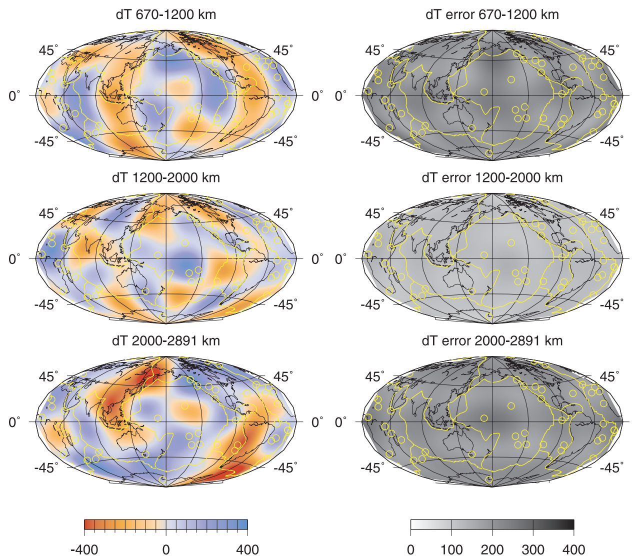


**Plate 5.** Relative variations, with respect to a thermochemical reference model, of temperature in the lower mantle [from *Trampert et al.*, 2004]. The exact reference model remains unknown due to nonunicity, given available constraints [e.g., *Deschamps and Trampert*, 2004]. The variations are likelihoods and are specified by Gaussian distributions. Shown are the mean (left column) and the standard deviation (right column) for different depth layers.

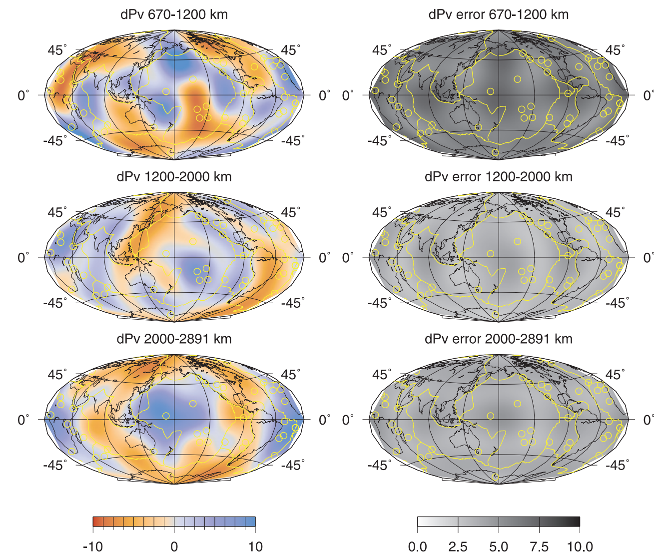


**Plate 6.** Same as for Plate 5, but for perovskite variations.

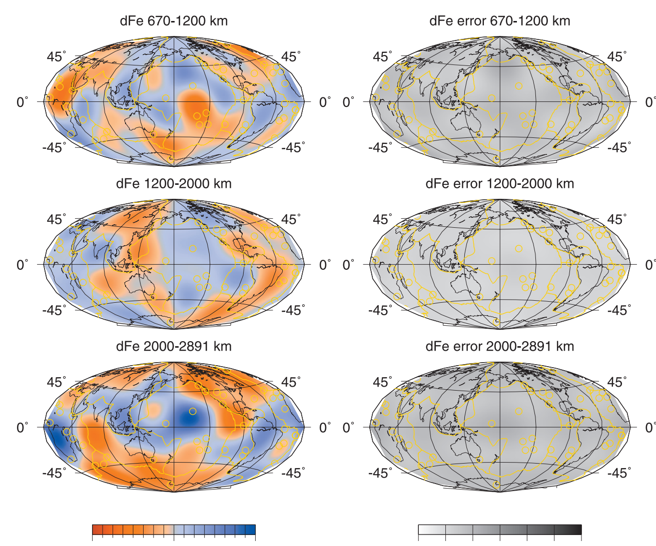


**Plate 7.** Same as for Plate 5, but for iron variations.

bulk sound are good proxies for iron and silicate variations, respectively; (v) compositional heterogeneity dominates buoyancy in the lowermost mantle, but even at shallower depths, its contribution to buoyancy is comparable to thermal effects; (vi) consistent with some previous suggestions [e.g., *Kellogg et al*., 1999] the so-called superplumes in the deep mantle beneath the central Pacific and southern Africa appear compositionally distinct and have a higher intrinsic density owing to enrichment in iron and perovskite; (vii) in contrast with earlier predictions, however, these and other structures of higher than average mass density in the lowermost mantle do not stand out as anomalously hot features but appear thermally neutral or even relatively cold.

## 6. DISCUSSION AND CONCLUDING REMARKS

Seismic tomography has been highly successful in delineating the lateral variations of propagation speeds of elastic waves in Earth's interior. Until a few years ago the emerging tomographically inferred patterns were mostly taken as proxies of spatial variations in temperature. However, it is increasingly evident that a quantitative interpretation of the currently available seismologic and mineral physics data sets cannot be done in the framework of temperature alone and that spatial variations in major element composition must be considered. This also implies that purely thermally driven convection models cannot be representative of the Earth.

Seismology has begun to produce increasingly compelling evidence for compositional heterogeneity at all scales in the mantle, and we expect that this trend will continue. But we need more than high-quality multiparameter imaging. Indeed, a quantitative characterization of tomographically inferred heterogeneity requires a careful uncertainty analyses of both the tomographic models and the mineral physics data. Probabilistic tomography, adopted recently to the mapping of very long wavelength (>10,000 km) structures in the mantle, can achieve just that.

The preliminary results of probabilistic tomography, summarized in section 5.4, can be used to test predictions of or expectations from thermochemical models that have recently been proposed to reconcile geophysical and geochemical observations. Thermochemical convection models that put all compositional heterogeneity in small blobs [*Becker et al*., 1999; *Helffrich and Wood*, 2001] do not explain the strong long-wavelength chemical variations unless the blobs are spatially concentrated by some (unspecified) mechanism. *Kellogg et al*. [1999] proposed a hot and intrinsically dense layer in the bottom 1000 or so km of the mantle. This layer would have a pronounced topography and be shaped rather passively through interactions with major downwellings (that is, slabs of subducted lithosphere). *Trampert et al.* [2004] confirm that the slow shear wave speed anomalies away from downwellings are indeed due largely due to increases in mass density; in contrast to *Kellogg et al*. [1999], however, they find them to thermally neutral or even relatively cold. Preliminary results of thermochemical convection modeling using the anelastic approximation [*Tackley*, 2002] suggest that a stable stratification over long periods of time is unlikely in the lowermost mantle [*Deschamps et al*., 2005], but the dynamics of this thermochemical system and, in particular, the implications for Earth's heat budget need further study. Furthermore, analyses of wave field distortion and scattering have so far not produced evidence for a sharp, global discontinuity between the upper-mantle transition zone and the base of the mantle [*Vidale et al*., 2001; *Castle and van der Hilst*, 2003]; therefore, a change in bulk properties—if any—would need to be more gradual than the sharp layer boundary implied by the Kellogg et al. model.

The collective seismological evidence (summarized in section 4) and the results of probabilistic tomography [*Trampert et al*., 2004; *Deschamps et al*., 2005] seem most consistent with models of thermochemical mantle evolution that are characterized by a radial stratification [*Anderson*, 2001, 2002] or zonation of heterogeneity and convective mixing, as suggested by *Albarède and van der Hilst* [2002] and consistent with the evolutionary model by *van Thienen et al.* [this volume], in combination, perhaps, with slow oscillatory motion of the piles of compositionally distinct materials in the deep mantle [*Davaille*, 1999].

Probabilistic tomography is still at its early stages and lines of improvement can readily be identified. Mass density is a crucial parameter to discriminate between temperature and compositional effects, but it is poorly constrained by seismological data, especially the odd degrees. To improve the estimates on density variations, we need to incorporate more independent constraints, including geodynamical data [*Forte and Mitrovica*, 2001] and specific density–sensitive modes measured from seismic records of exceptionally strong recent earthquakes. Depth parameterization needs to be refined, but this increases the size of the model space and thus computer time. With the rapid advance of computer technology, we hope that parallel programming can effectively achieve this in the near future. It is further essential to include body wave information into the full-model space search. Classical tomography can more easily move towards data integration but needs to shy away from mere imaging, in order to improve local parameter estimation and to get error analyses on a more quantitative footing. A further target of concerted mineral physics and seismological research is the determination of the scale length of elastic and compositional heterogeneity in and between the thermochemical boundary layers of mantle convection. Refining the models including anisotropy and anelasticity will become essential to increasing the seismologic information. Careful Earth parameterization, the use of finite frequency kernels [*Dahlen et al*., 2000], wavefield scattering and multiresolution analysis [e.g., *De Hoop and van der Hilst*, 2005], and adjoint methods [*Tromp et al*., 2005] will no doubt prove crucial in this ambitious but exciting endeavour.

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