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3D STRUCTURE OF THE EARTH'S LOWER MANTLE

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Abstract. We present an overview of the present knowledge of the earth's lowermantle 3D structure, as currently obtained owing to progress, in the last ten years, in seismic tomography as well as forward modelling of seismic travel times and waveforms. We discuss constraints that seismic modelling brings to the debate concerning major geodynamical questions, in particular the issue of global "1 layer" or "2 layer" circulation, of the missing geochemical reservoir, as well as of the role in global dynamics of the thermo-chemical boundary layer at the base of the mantle. © 2001 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

Structure tri-dimensionnelle du manteau inférieur de la terre

Résumé. *Nous présentons une revue de l'état actuel des connaissances sur la structure 3D du manteau inférieur de la terre, obtenu grâce aux progrès, dans les dix dernières années, de la tomographie sismique ainsi que de la modélisation directe des temps de parcours et des formes d'onde sismiques. Nous discutons les contraintes apportées par la modélisation sismique au débat concernant les questions géodynamiques majeures, en particulier celle de la circulation à "une" ou "deux" couches, celle du réservoir géochimique manquant, ainsi que celle du rôle dans la dynamique globale, de la couche limite thermo-chimique à la base du manteau.* © 2001 Académie des sciences/Éditions scientifiques et médicales Elsevier SAS

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1. Introduction

The earth's solid mantle is about 2900 km thick and is divided into upper and lower mantle. The lower mantle comprises the region located between the seismically defined discontinuity at 670 km depth and the core-mantle boundary (CMB) at 2900 km depth. It represents 70% of the volume of the mantle and is still at the center of one of the most fundamental debates in solid earth geophysics, which concerns the character of the global circulation which drives plate tectonics: are there mostly separate circulations in the upper and the lower mantle, or is there significant mixing across the 670 km discontinuity? A related question is whether there is a relatively undisturbed, primordial reservoir rich in radioactive elements within the lower mantle, which might account for the missing heat in the global heat budget of the earth.

The lowermost mantle is thought to play a key role in global dynamics, as there is both a chemical and thermal boundary layer, between the solid (silicate) mantle and the liquid (iron) core. Unravelling the nature, horizontal and vertical scale lengths of lateral heterogeneity in the bottom several hundred kilometers has been the goal of many seismological studies in recent years, as the increase in quality of data and global sampling has gradually led to improved resolution.

The lowermost 200-300 km or so above the CMB, have long been known to be distinct from the rest of the mantle: early seismic travel time studies documented a change in the velocity gradient as a function of depth for both P and S waves, and the name D" given to this region by Bullen (1949) has survived to this day. Evidence found in the early 1980's for a seismic discontinuity around 250 km above the CMB, interpreted as the top of D" (Lay and Helmberger, 1983), further defined this region as a distinct region of the mantle, even though this discontinuity is not detected globally. Over the last 20 years, it has been shown that D" is heterogeneous and organized at various scale-lengths: from tens of km (using scattered waves) to tens of thousands of km (from seismic tomography). Recent forward modeling results of seismic body wave phases also indicate sharp and well defined horizontal gradients across structural domains on scale-lengths of several hundred km.

In what follows, we briefly review recent contributions to our knowledge about the structure and dynamics of the lower mantle from seismic tomography, the study of scattered waves, as well as forward modeling of travel times and waveforms of body waves. More extended reviews focused on D" can be found in Lay et al. (1998) and Garnero (2001).

2. Seismic tomography and the deep mantle

The principle of seismic tomography is similar to that of medical imaging: travel times or attenuation of certain types of waves are measured on crossing paths from many sources to many receivers allowing to locate and determine the shape and amplitude of three dimensional (3D) "anomalies" with respect to a standard reference model. Global seismic models are obtained using natural seismicity as sources of elastic waves and data collected at seismographic stations all over the world. A regrettable limitation is the uneven distribution of sources (mostly along tectonic plate boundaries) and stations (mostly on continents) which introduces severe limitations in the resolution of deep 3D structure. As there are two types of elastic waves, compressional (P) and shear (S), there are also presently two main types of tomographic models. "P-models" are generally constructed using bulletin data, collected by the International Seismological Centre (ISC) in the U.K. (e.g. Bijwaard et al., 1998; Karason and vander Hilst, 2001; Boschi and Dziewonski, 2000). They rely heavily on first arrival travel time data, which are the most consistently reported, and therefore have best resolution around subduction zones, where both the density of stations and sources is highest. "S-models" are constructed using travel times and waveforms of S waves collected over the last 15 years at broadband stations of the international global seismic network, of which the french led GEOSCOPE (Romanowicz et al., 1991; Montagner et al., 1998) is a significant component. While P velocity (V_p) tomographic models are able to resolve fine details of structure in the vicinity of subduction zones (Figure 1), the long wavelength features of lower mantle structure are best constrained in global tomographic models of S velocity (V_s), because of the more uniform global sampling they attain, in particular under the oceans, since there are more data types available. Global 3D V_s models consistently indicate an increase in the strength of lateral heterogeneity in the lowermost 500 km of the mantle, mirroring, to some extent, what is observed at lithospheric depths, i.e. at the earth's top boundary layer (Figure 2). There is also a distinct change in the character of lateral heterogeneity, as expressed in its spectrum, which is relatively rich in short wavelengths (i.e. ”white”) throughout the bulk of the lower mantle, but becomes progressively dominated by low degrees as depth increases. In the lowermost 400-500km of the mantle, degree 2 clearly stands out (Figure 3). The striking long wavelength features that give rise to this strong ”degree 2” are two large regions of low velocity, centered in the Pacific and under Africa, and surrounded by a ring of high velocities (Figure 4). The latter is thought to be related to remnant slab material that has piled up at the bottom of the mantle over geological times, as seen in geodynamic simulations (e.g. Ricard et al., 1993). However, the connection between obliquely plunging downgoing lithospheric slabs at the top of the lower mantle, and the high velocity structure in the circum Pacific ring at the base of the mantle, is relatively clear only for some very specific profiles in P velocity models (e.g. central America, Karason and van der Hilst (2001)) and only in some S velocity models (Figure 5). In fact, in most regions where they don't lie flat at the upper-mantle/lower-mantle boundary, slabs can be followed down no further than about 1500km. This has led Fukao et al. (2001) to conjecture that a major ”flushing” event may have occurred about 45 M years ago and caused a gap between older, remnant slabs piled up at the CMB, and the currently observable, continuous subducting lithosphere.

The two prominent regions of low velocities at the base of the mantle have been identified as regions of major thermal upwelling and are referred to as ”superplumes”. Most tomographic S models indicate that these upwellings rise high above the CMB, but become significantly narrower at depths greater than 500 km above the CMB (Figure 6), and some models distinctly indicate that they extend at least to the top of the lower mantle (e.g. SAW24B16, Mégnin and Romanowicz, 2000). Also, the tilt observed on some SW-NE sections through the African plume (Ritsema et al., 1999) may be an artifact due to smearing effects associated with preferential directions of sampling in some models. Recently, in a tomographic study of upper mantle attenuation, we have shown evidence for a vertical continuation into the upper mantle of the high temperature anomalies associated with the Pacific and African superplumes (Romanowicz and Gung, 2002).

There is increasing evidence that these ”superplumes” also involve a component of chemical heterogeneity, at least at their base. This evidence comes from the joint tomographic inversion of seismic data sensitive to V_p and V_s, which allows the inspection of depth variations in the ratio $R = dlnV_s/dlnV_p$, as well as the comparison of structure in V_s and in bulk sound velocity (V_Φ), which both give insight into the chemical/thermal nature of heterogeneity. The ratio R, which is on the order of $R \sim 1.7$ in the upper mantle, has been shown to increase in the lower mantle, reaching values between 3 and 4 at depths of 2000 km and larger (e.g. Robsertson and Woodhouse, 1996; Masters et al., 2000; Romanowicz, 2001). When confronted with the results of mineral physics experiments, such high values, well in excess of $R = 2.5$, cannot be explained by thermal effects alone, even when including pressure and anharmonic effects (Agnon and Bukowinski, 1990; Karato and Karki, 2001). At depths greater than 2000km, the correlation between large scale V_s and V_p distributions becomes increasingly poorer (e.g. Robertson and Woodhouse, 1996) and the long wavelength V_Φ distribution is anti-correlated with that of V_s (Su and Dziewonski, 1997; Ishii and Tromp, 1999). All these results are difficult to explain without invoking a compositional component to the heterogeneity in the deepest mantle.

A provocative suggestion by Ishii and Tromp (1999) has led to the controversial issue, whether the large scale density structure at the base of the mantle is correlated or anticorrelated with the velocity structure. In their recent normal mode study, Ishii and Tromp (1999) suggested that, in D”, the low-velocity, ”superplume” regions in the central Pacific and under Africa may correspond to higher than average density. While normal mode spectra from very large deep earthquakes have some sensitivity to the longest wavelengths of lateral variations in density, this sensitivity is weak, and other studies have shown that the density structure, and in particular, the nature of its correlation with velocity structure, depends strongly on initial and regularization constraints on the inversions (e.g. Resovsky and Ritzwoller, 1999; Romanowicz, 2001; Kuo and Romanowicz, 2002). Whether the density structure at the base of the mantle is such as advocated by Ishii and Tromp (1999) therefore remains unresolved.

Although the anticorrelation of V_s and V_Φ at the base of the mantle can be reconciled with dynamical models of thermal and chemical heterogeneity that imply buoyant material associated with the two major African and Pacific upwellings (Forte and Mitrovica, 2001), the possibility of dense material residing at the base of these superplumes has intrigued geodynamicists and has motivated recent numerical (e.g. Mc Namara and van Keken, 2000) as well as laboratory (e.g. Davaille, 1999) experiments. Such experiments also relate to renewed interest in the possible existence of a chemically distinct reservoir in the lower mantle (Kellogg et al., 1999). In order to satisfy the global geochemical and thermal data, which seem to imply a considerable ”missing” volume of material enriched in radioactive elements, somewhere in the earth, this layer would have to be much thicker than D” in the regions of upwellings, and present an upper boundary with significant topography. No seismological evidence for such a boundary in the lower mantle has been found until now, and, as we have seen, the morphology of the superplumes tends to indicate that they are wide-based in D”, but tend to become narrower as they rise into the lower mantle (Figure 6). This implies that the volume available within the superplumes for the geochemical reservoir may not be large enough.

A number of studies have used differential travel times of phases sensitive to the base of the mantle (core or diffracted phases), referenced to core phases in order to minimize contributions from the upper mantle, in order to map lateral variations of structure in D”. These studies have confirmed the large scale variations observed from whole mantle tomography, and in particular some regional discrepancies between S and P models (e.g. Wysession, 1996; Sylvander and Souriau, 1996a,b).

3. Forward modelling: a complementary approach to tomography

While seismic tomography presently gives consistent information on the large scale structure in the deep mantle, uneven spatial coverage, particularly at large depths in the mantle, combined with errors in the data and imperfections in the theory impose damping conditions in tomographic inversions that prevent accurate recovery of the amplitudes and gradients of lateral heterogeneity. Insight into both the strength of heterogeneity as well as the true length scales can be obtained through the use of forward modelling, presently limited to specific well sampled ”corridors”.

One such well sampled region is the central Pacific ocean, which lies in a favorable geometry for paths between the highly seismic Fiji-Tonga subduction zone and north America, populated by numerous broadband stations at appropriate epicentral distances for the observation of diffracted waves interacting with the Pacific superplume. Forward modelling of S, Sdiff and ScS travel times (relative to reference phases such as SKS to minimize contributions from upper mantle structure) has shown that existing tomographic models are able to successfully reproduce the observed trends of travel times (as referenced to a spherically symmetric model) with distance, but they fail to provide good estimates of the amplitudes of the variations observed (e.g. Bréger et al., 1998). In fact, tomographic models underestimate these variations by a factor of two or three. By starting with a global tomographic model and keeping the shape of the anomalies approximately fixed, it is possible to obtain a much better fit to the observed travel times by simply modifying the amplitudes in parts of and immediately above D”(e.g. Bréger and Romanowicz, 1998). The resulting ”modified” models exhibit lateral variations in S velocity at the base of the mantle that reach on the order of 8-10% over distances of several hundred kilometers, implying strong lateral gradients of structure on the borders of the Pacific superplume. Such studies also shows that the strongly reduced velocities associated with the superplume continue to large heights above the CMB (possibly 1000 km, Figure 7), and confirms that this superplume is characterized by a broad base which becomes narrower as it rises into the lower mantle (Bréger et al., 2001).

Similar results have been found under Africa, in the region bordering the African superplume, along profiles made possible by the deployment of the temporary Tanzania PASSCAL array (e.g. Ritsema et al., 1998b; Wen et al., 2001). In particular, detailed waveform modeling of the African data reveals extremely sharp boundaries on both sides of the superplume (Ni et al. 2002). Such strong lateral gradients cannot be explained by thermal effects alone and therefore imply the existence of chemical heterogeneity at the base of the mantle. A contributing factor, especially when comparing P versus S sensitive data, could also be anisotropy, as suggested by Wysession et al. (1999) to explain rapid decrease of the ratio of V_p to V_s towards Alaska, in the northern Pacific.

4. Anisotropy in D"

Seismic anisotropy, indicative of strong past or present shear associated with convective motions, has been shown to be strong in the upper mantle. On the other hand, the bulk of the lower mantle is, within the limits of the present day resolution, devoid of any indication of anisotropy (e.g. Meade et al., 1995). In contrast, there is now ample evidence for the presence of anisotropy in D". Vinnik et al. (1989) first suggested that the observation of elliptically polarized diffracted S waves(S_{diff}) was due to anisotropy in D", along paths sampling the central Pacific ocean. The presence of anisotropy was later confirmed by other studies of Sdiff or ScS in the same region (e.g. Vinnik et al., 1995, 1998; Russell et al., 1998; Ritsema et al., 1998a) as well as in the circum Pacific region (Kendall and Silver, 1996; Matzel et al., 1996; Garnero and Lay, 1997). In most cases, SH leads SV, implying horizontal layering or flow, however, short scale variations have been found and interpreted as evidence of complex shear flows, possibly associated with partial melt, at the root of the Pacific superplume (Russell et al., 1998).

5. ULVZ

Perhaps the most intriguing recent discovery regarding the lowermost mantle, is that of patches of extremely reduced P velocity near the CMB, called "ultra low velocity zones" (ULVZ), indicative of the existence, albeit intermittent, of a thin basal mantle layer of thickness 10-40 km with corresponding reductions in P velocity on the order of 10%. First detected in the central Pacific from the analysis of travel times of the phase SP_dKS, whose P_d leg travels a short distance along the CMB (Garnero and Helmberger, 1995), they have now been found in different locations (e.g. Helmberger et al., 2000), although most of the surface of the CMB where such studies have been possible so far do not show any evidence of ULVZ's (e.g. Williams et al., 1998). A possible correlation of the locations of ULVZ's with the hotspot distribution has been proposed (Figure 8). The existence of a thin basal layer is also suggested from the study of travel times of short-period diffracted P (P_{diff}), which indicates an average reduction in P velocity of at least 4% at the very base of the mantle, compared to reference global models (e.g. Sylvander et al., 1997). Some authors propose a related reduction in V_s of up to 30% (e.g. Williams and Garnero, 1996; Ni and Helmberger, 2001), which favors a partial melting interpretation. However, other studies find o evidence for an equivalent reduction in S velocity (e.g. Stutzmann et al., 2000; Castle and van der Hilst, 2000).

While the absence of an ULVZ in V_s associated with the one in V_p is puzzling, various interpretations for this basal layer of dramatically lower V_p velocities have been proposed. These include partial melting (on the order of 5-30% in volume, Williams and Garnero, 1996; Wen and Helmberger, 1998) and/or infiltration of iron from the core (Manga and Jeanloz, 1996). The observed effects could also originate in a thin zone of finite rigidity at the top of the outer core (e.g. Garnero and Jeanloz, 2000; Buffett et al., 2000). Whatever their origin, the strong lateral variations in the vicinity of the CMB are indicative of processes which involve core-mantle interactions, and this should provide important implications on mantle dynamics.

6. Short scale heterogeneity in the deep mantle

As we have seen, the bulk of the lower mantle is, according to tomographic results, characterized by relatively short wavelength heterogeneity, the details of which are not very well resolved. On the other hand, except in regions of subduction, there is little evidence for coherent energy originating from subhorizontal reflectors deeper than the 670 km discontinuity: slowness/frequency stacks generally appear very quiet in front of major upper-mantle discontinuity reflected phases, all the way back to D" depths, except for anecdotal evidence such as that for a deeper reflector under southern Africa (e.g. Le Stunff et al., 1995) or sub-vertical reflectors suggestive of ancient subducted lithosphere near the Mariana arc (e.g. Kaneshima and Hellfrich, 1999). In contrast, studies of precursors to core phases (PKP) indicate strong scattering in D" (e.g. Bataille and Flatté, 1988; Hedlin and Shearer, 2000), although some questions remain as to the vertical extent of the scattering region, which may reach high above D" (Hedlin et al., 1997).

In addition, numerous studies have documented the existence of a sub-horizontal reflector at depths of about 250 ± 100 km above the CMB, more often observed for S waves than for P waves (e.g. Wysession et al., 1998). This reflector does not seem to correspond to any plausible mineralogical phase change and some have questioned its classification as a "discontinuity", arguing that it could be an artifact of the effects of strong 3D heterogeneity in D" on wave propagation (e.g. Tromp and Dziewonski, 1998).

7. Conclusions

While the bulk of the lower mantle 3D structure remains poorly resolved, so that agreement has not yet been reached on whether subducted slabs can be traced down to the core-mantle boundary and whether major upwellings reach into the upper mantle, many seismological studies converge to indicate that strong heterogeneity is present in D", and, in some regions, extends to at least a thousand km above the CMB. There is now unequivocal evidence for strong gradients of structure in D" that cannot be explained by thermal effects alone, as well as extensive evidence for anisotropy, the precise origin of which is however not well resolved due to limitations in the sampling afforded by the present day dataset. It is thus now practically established that the nature of heterogeneity in the lowermost mantle is both thermal and compositional, and the presence of ULVZ's implies some degree of partial melt and/or mixing with iron from the core. Because the strongest heterogeneity appears to be largely confined to the lowermost few hundred km of the mantle, it is not clear whether a distinct lower mantle geochemical reservoir of sufficient volume is compatible with the seismic data, as much of it would have to be undetected by seismic methods. On the other hand, the African and Pacific superplumes appear to be associated not only with the upwelling of hotter than average material, but also may comprise a chemically distinct core. An emerging view, from the combination of velocity and attenuation tomography, is that the thermal anomaly persists well into the upper mantle (through the transition zone) while the chemical "root" may remain confined to the lowermost mantle, which may explain why the superplumes are so much more prominently visible in D".

Future progress in mapping lower mantle structure relies on increased seismic resolution, and in particular, better sampling under the oceans, which will require sustained efforts to establish long term ocean floor observatories.

8. Figure Captions

Figure 1. Examples of depth cross sections in several subduction zone areas, showing fast anomalies associated with subducted slabs, as revealed by P travel time tomography using ISC data (from Karason and vanderHilst, 2000). These studies reveal that in some regions slabs are able to penetrate deep into the lower mantle (AA', DD', EE',FF'), while in others they appear to stagnate at the 670 km discontinuity (BB',CC').

Figure 1. Exemples de coupes verticales à travers quelques zones de subduction, montrant les abnomalies de vitesses rapides associées avec les plaques plongeantes, obtenues par tomographie d'ondes P à partir de données de bulletins ISC (d'après Karason et vanderHilst, 2000). Ces études montrent que dans certaines régions, les plaques pénètrent assez profondément dans le manteau inférieur (AA', DD', EE',FF'), alors que dans d'autres régions, elles semblent s'étaler au dessus de la discontinuité de 670 km (BB',CC').

Figure 2. Depth profiles of rms S velocity for different recent global tomographic models: SAW24B16 (Mégnin and Romanowicz, 2000); SB4L18 (Masters et al., 1996); S362D1 (Gu et al., 2001); S20RTS (Ritsema et al., 1999); TXBW (Grand, 2002).

Figure 2. Variation avec la profondeur de la rms en V_s pour differents modèles tomographiques récents: SAW24B16 (Mégnin and Romanowicz, 2000); SB4L18 (Masters et al., 1996); S362D1 (Gu et al., 2001); S20RTS (Ritsema et al., 1999); TXBW (Grand, 2002).

Figure 3. Spectrum of lateral heterogeneity in different depth ranges, up to spherical harmonic degree 16, in the lower mantle, for tomographic models SAW24B16 (Mégnin and Romanowicz, 2000), S362D1 ((Gu et al., 2001) and S20RTS (Ritsema et al., 1999). While some significance difference exist in the level of each harmonic between models, it is clear that the bottom 500 km of the mantle are largely dominated by degree 2, in contrast to the rest of the lower mantle, where smaller scale features are proportionately more important.

Figure 3. Spectre des hétérogénéités latérales jusqu'au degré 16 en harmoniques sphériques, pour différents domaines de profondeur dans le manteau inférieur, pour les modéles tomographiques SAW24B16 (Mégnin and Romanowicz, 2000), S362D1 ((Gu et al., 2001) et S20RTS (Ritsema et al., 1999). Malgré des différences significatives entre les amplitudes des harmoniques individuels entre les modèles, il est clair que les 500 km à la base du manteau sont dominés par le degré 2, contrairement au reste du manteau inférieur, où les petites échelles ont proportionellement plus d'importance.

Figure 4. Comparison of maps of S velocity heterogeneity at 2000 km and 2770 km depth for the same models as considered in Figure 1 (the scale is in % relative to the average velocity at each depth). Note the change in the character of heterogeneity in the vicinity of the CMB: amplitudes increase significantly, and the distribution is shifted to longer wavelengths. The two major low velocity regions ("superplumes") visible at 2770 km depth in the central Pacific and under Africa continue upward in most models, but the core of the anomaly becomes much narrower, as can be seen at 2000 km depth in the three top models.

Figure 4. Comparison de cartes d' hétérogénéité pour la vitesse des ondes S aux profondeurs de 2000 et 2770 km, pour les mêmes modèles considérés dans la Figure 1 (échelle en % par rapport à la vitesse moyenne à chaque profondeur). Notez le changement de style des hétérogénéités à l'approche de la limite noyau-manteau (CMB): les amplitudes augmentent significativement, et la distribution est déplacée vers les grandes longueurs d'onde. Les deux régions majeures de vitesse lente ("superplumes") visibles à 2770 km de profondeur sous le Pacifique central et sous l'Afrique se prolongent vers le haut dans la plupart des modèles, mais la zone de forte anomalie devient beaucoup plus étroites, comme on le voit à la profondeur de 2000 km pour les trois modèles du haut.

Figure 5. Comparison of depth cross-sections across central America, a region of fast velocities in the lower mantle, for the five S velocity models considered in Figures 1 and 3.

Figure 5. Comparaison de coupes en fonction de la profondeur à travers l' Amérique centrale, une région de vitesses sismiques rapides dans le manteau inférieur, pour les cinq modèles de vitesses V_s déjà présentés dans les Figures 1 et 3.

Figure 6. Comparison of depth cross-sections across the African "superplume" for the five S velocity models considered in Figures 1 and 3.

Figure 6. Comparaison de coupes en fonction de la profondeur à travers la "superplume" africaine pour les cinq modèles V_s déjà présentés dans les Figures 1 et 3.

Figure 7. A) Depth cross-section along a path from Fiji-Tonga to North America for a modified mantle model that explains S-SKS travel time residuals. B) same as A) for the for the original tomographic model (SAW12D, Li and Romanowicz, 1996). (from Bréger and Romanowicz, 1998).

Figure 7. A) profil en fonction de la profondeur le long d'un trajet entre Fiji-Tonga et l'Amérique du Nord, pour un modèle du manteau modifié qui explique les anomalies de temps de parcours S-SKS; B) Même profil que pour A) pour le modèle tomographique d'origine (SAW12D, Li and Romanowicz, 1996). (d'après Bréger et Romanowicz, 1998).

Figure 8. Map showing regions in D" where Ultra Low Velocity Zones (ULVZ's) have (red) or have not (blue) been detected. These regions are represented by the geographical extension of the Fresnel zones

corresponding to the observed SP_dKS waves. A correlation with the location of major hotspots, marked by white circles of size proportional to the estimated hot spot flux, has been suggested (Williams et al., 1998). Courtesy of Ed Garnero.

Figure 8. Carte montrant les régions de D" où ont été détectées (rouge) ou non détectées (bleu) les ULVZ. Ces régions sont représentées par les zones de Fresnel correspondant aux ondes SP_dKS observées. Une corrélation a été suggérée avec la distribution des principaux hot spots, indiqués par les cercles blancs de taille proportionnelle au flux correspondant estimé (Williams et al., 1998). Source: Ed Garnero.

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References

[1] Agnon A., Bukowinski M., δ_s at high pressure and $dlnV_s/dlnV_p$ in the lower mantle, Geophys. Res. Lett. 17(1990) 1149-1152.

[2] Bataille, K. and S. M. Flatté, Inhomogeneities near the core-mantle boundary inferred from short period scattered PKP waves recorded at the global digital seismograph network, J. Geophys. Res. 93(1988) 15,057-15,064.

[3] Bijwaard, H., W. Spakman and E. R. Engdahl Closing the gap between regional and global travel time tomography, J. Geophys. Res. 103(1998) 30,055-30,078.

[4] Bolton, H. and G. Masters, Travel times of and S from the global digital seismic networks: implications for the relative variation of P and S velocity in the mantle, J. Geophys. Res. 106(2001) 13,527-13,540.

[5] Boschi, L. and A. M. Dziewonski, Whole Earth tomography from delay times of P, PcP, and PKP phases: Lateral heterogeneities in the outer core or radial anisotropy in the mantle?, J. Geophys. Res. 105(2000) 13,675-13,696.

[6] Bréger, L. and B. Romanowicz, Thermal and chemical 3D heterogeneity in D", Science 282(1998) 718-720.

[7] Bréger, L., B. Romanowicz and L. Vinnik, Tests of tomographic models in D" using differential travel times, Geophys. Res. Lett. 25(1998) 5-8.

[8] Bréger, L., B. Romanowicz and C. Ng, The Pacific plume as seen by S, ScS, and SKS, Geophys. Res. Lett. 28(2001) 1107-1110.

[9] Buffett, B. A., Garnero, E. J., Jeanloz, R., Sediments at the top of Earth's core, Science 290(2000) 1338-1342.

[10] Bullen, K. E., Compressibility-pressure hypothesis and the Earth's interior, MNRAS Geophys. Suppl 5(1949) 355-368.

[11] Castle, J. C. and R. D. van der Hilst, The core-mantle boundary under the Gulf of Alaska: no ULVZ for shear waves, Earth Planet. Sci. Lett. 176 (2000) 311-321.

[12] Davaille, A., Simultaneous generation of hotspots and superswells by convection in a heterogeneous planetary mantle, Nature 402(1999) 756-760.

[13] Forte, A. and J. Mitrovica , Deep-mantle high-viscosity flow and thermochemical structure inferred from seismic and geodynamic data, Nature 410(2001) 1049-1056.

[14] Fukao, Y., S. Widiyantoro and M. Obayashi, Stagnant slabs in the upper and lower mantle transition region, Rev. of Geophys. 39(2001) 291-323.

[15] Garnero, E. J., Heterogeneity of the lowermost mantle, Annu. Rev. Earth Planet. Sci. 28(2001) 509-537.

[16] Garnero, E. J. and D. V. Helmberger, A very slow basal layer underlying large-scale low velocity anomalies in the lower mantle beneath the Pacific: evidence from core phases, Phys. Earth Planet. Int. 91(1995) 161-176.

[17] Garnero, E. J. and T. Lay, Lateral variations in lowermost mantle shear wave anisotropy beneath the north Pacific and Alaska, J. Geophys. Res, 102(1997) 8121-8135.

[18] Garnero, E. J., Jeanloz, R., Fuzzy Patches on the Earth's Core-Mantle Boundary?, Geophys. Res. Lett. 27(2000), 2777-2780.

[19] Grand S.P., Mantle shear wave tomography and the fate of subducted slabs, Phil. Trans. R. Soc. of London(2002) in press.

[20] Gu, Y. J., A.. M. Dziewonski, W.-J. Su, and G. Ekström, Models of the mantle shear velocity and discontinuities in the pattern of lateral heterogeneities, J. Geophys. Res. 106(2001) 11169-11199.

[21] Hedlin, M. A., P. A. Shearer and P. S. Earle Seismic evidence for small-scale heterogeneity throughout the Earth's mantle, Nature 387(1997) 145-150.

[22] Hedlin, M. A., Shearer, P. M., An analysis of large-scale variations in small-scale mantle heterogeneity using Global Seismographic Network recordings of precursors to PKP, J. Geophys. Res., 105(2000) 13,655-13,673.

[23] Helmberger, D., S. Ni, L. Wen and J. Ritsema, Seismic evidence for ultralow-velocity zones beneath Africa and eastern Atlantic, J. Geophys. Res. 105(2000) 23,865-23,878.

[24] Ishii M., Tromp J., Normal-mode and free-air gravity constraints on lateral variations in velocity and density of the Earth's mantle. *Science*, 285(1999), 1231-1236.

[25] Kaneshima, S. and G. Hellfrich, Dipping low-velocity layer in the mid-lower mantle: evidence for geochemical heterogeneity, Science 283(1999) 1888-1891.

[26] Karason, H. and R. vander Hilst, Improving global tomography models of P-wavespeed I: incorporation of differential travel times for refracted and diffracted core phases (PKP,Pdiff), J. Geophys. Res 106(2001) 6569-6587.

[27] Karato S, Karki B., Origin of lateral heterogeneity of seismic wave velocities and density in Earth's deep mantle, J. Geophys. Res. 106(2001), 21,771-21,783.

[28] Kellogg, L., B. Hager and R. van der Hilst, Compositional stratification in the deep mantle, Science 283(1999) 1881-1884.

[29] Kendall, J. M. and P. G. Silver, Constraints from seismic anisotropy on the nature of the lowermost mantle, Nature 381(1996) 409-412.

[30] Kuo C., Romanowicz B., On the resolution of density anomalies in the Earth's mantle using spectral fitting of normal mode data. Geophys. J. Inter. (2002) in press.

[31] Lay, T. and Helmberger, D. V., A lower mantle S-wave triplication and the shear velocity structure of D", Geophys. J. R. Astron. Soc. 75(1983) 799-838.

[32] Lay, T., Williams Q., Garnero, E. J., The core-mantle boundary layer and deep Earth dynamics, Nature 392(1998), 461-468.

[33] LeStunff, Y., C. Wicks and B. Romanowicz, P'P' precursors under Africa: a broadband investigation, Science 270(1995) 74-77.

[34] Li, X-D., and B. Romanowicz, Global mantle shear velocity model developed using nonlinear asymptotic coupling theory, J. Geophys. Res. 101(1996) 101 22,245-22,273.

[35] Manga, M. and R. Jeanloz, Implications of a metal-bearing chemical boundary layer in D" for mantle dynamics, Geophys. Res. Lett. 23(1996) 3091-3094.

[36] Masters G., Johnson, S., Laske, G. and Bolton, B., A shear-velocity model of the mantle, Philos. Trans. R. Soc. Lond. A 354(1996) 1,385-1,411.

[37] Masters G, Laske G, Bolton H, Dziewonski A. M., The relative behavior of shear velocity, bulk sound speed, and compressional velocity in the mantle: implications for chemical and thermal structure, In *Earth's deep Interior: mineral physics and tomography from the Atomic to the Global Scale*, ed. S Karato et al., AGU, Washington, D.C., *Geophys. Monogr. Ser.*, 117(2000) 63-87,

[38] Matzel, E. ,M. K. Sen and S. P. Grand, Evidence for anisotropy in the deep mantle beneath Alaska, Geophys. Res. Lett. 23(1996) 2417-2420.

[39] McNamara A. K., van Keken P.E., Cooling of the Earth: a parameterized convection study of whole vs. layered models, Geochem. Geophys. Geosys. 1(2000), 2000GC000045.

[40] Meade, C., P.G. Silver and S. Kaneshima, Laboratory and seismological observations of lower mantle isotropy, Geophys. Res. Lett. 22(1995), 1293-1296.

[41] Mégnin, C. and B. Romanowicz, The 3D shear velocity structure of the mantle from the inversion of body, surface and higher mode waveforms, Geophys. J. Inter. 143(2000) 709-728.

[42] Montagner J.P., P. Lognonné, J.-F. Karczewski, G. Roult, E. Stutzmann, and R. Beauduin, Towards a multiscalar and multiparameter network for the next century, the French efforts, Phys. Earth Planet. Int. 108(1998) 155-174.

[43] Ni, S., and D. Helmberger, Probing an ultra-low velocity zone at the core mantle boundary with P and S waves, Earth Planet. Sci. Lett. 187(2001) 301-310.

[44] Ni, S., E. Tan, M. Gurnis and D. Helmberger, Sharp sides to the African Superplume, Science 296(2002) 1850-1852.

[45] Resovsky J. S., Ritzwoller M. H., Regularization uncertainty in density models estimated from normal mode data, Geophys. Res. Lett, 26(1999), 2319-2322.

[46] Ricard, Y., M. A. Richards, C. Lithgow-Bertelloni, Y. Le Stunff, A geodynamical model of mantle density heterogeneity, J. Geophys. Res 98(1993) 21,895-21,909.

[47] Ritsema, J., Lay, T., Garnero, Ed., Benz, H., Seismic anisotropy in the lowermost mantle beneath the Pacific, Geophys. Res. Lett. 25(1998a) 1229-1232.

[48] Ritsema, J., S. Ni , D. V. Helmberger, and H.P. Crotwell, Evidence for strong shear velocity reductions and velocity

gradients in the lower mantle beneath Africa, Geophys. Res. Lett. 25(1998b) 4245-4248.
[49] Ritsema, J. , H. van Heijst and J. Woodhouse, Complex shear wave velocity structure imaged beneath Africa and Iceland, Science 286(1999) 1925-1928.
[50] Robertson G. S., Woodhouse J. H., Ratio of relative S to P velocity heterogeneity in the lower mantle, J. Geophys. Res. 101(1996) 20,041, 20,052.
[51] Romanowicz B.,J.F. Karczewski, M. Cara, P. Bernard, J. Borsenberger, B. Dole, D. Fouassier, J.C. Koenig, M. Morand, R. Pillet, A. Pyrolley and D. Rouland., The Geoscope program: present status and perspectives, Bull. Seism. Soc. Am., 81(1991) 243-264.
[52] Romanowicz B., Can we resolve 3D density heterogeneity in the lower mantle? Geophys. Res. Lett. 28(2001) 1107-1110.
[53] Romanowicz, B. and Y.C. Gung, Superplumes from the core-mantle boundary to the lithosphere: implications for heat-flux, Science 296(2002) 513-516.
[54] Russell, S., T. Lay and E. J. Garnero, Seismic evidence for small-scale dynamics in the lowermost mantle at the root of the Hawaian hotspot, Nature 396(1998) 255-258.
[55] Stutzmann, E. L. Vinnik, A. Ferreira, and S. Singh, Constraint on the S-wave velocity at the base of the mantle. Geophys. Res. Lett. 27(2000) 1571-1574.
[56] Su W. J., Dziewonski A. M., Simultaneous inversion for 3-D variations in shear and bulk velocity in the mantle, Phys. Earth Planet. Inter. 100(1997), 135-156.
[57] Sylvander, M., and A. Souriau Mapping S-velocity heterogeneities in the D” region, from SmKS differential travel times, Phys. Earth Planet. Inter. 94(1996a) 1-21.
[58] Sylvander, M., and A. Souriau P-velocity structure of the core-mantle boundary region inferred from PKP(AB)-PKP(BC) differential travel times, Geophys. Res. Lett. 23(1996b) 853-856.
[59] Sylvander, M., B. Ponce and A. Souriau, Seismic velocities at the core-mantle boundary inferred from P waves diffracted around the core, Phys. Earth. Planet. Int. 101(1997) 189-202.
[60] Tromp, J. and A. M. Dziewonski, Two views of the deep mantle, Science 281(1998) 655-656.
[61] Vinnik, L., V. Farra and B. Romanowicz, Observational evidence for diffracted SV in the shadow of the earth’s core, Geophys. Res. Lett. 16(1989) 519-522.
[62] Vinnik, L., B. Romanowicz, Y. LeStunff and L. Makeyeva, Seismic anisotropy in the D” layer, Geophys. Res. Lett. 22 (1995) 1657-1660.
[63] Vinnik, L., L. Bréger and B. Romanowicz, Anisotropic structures at the base of the mantle, Nature 393(1998), 564-567.
[64] Wen, L., Helmberger, D. V., Ultra-low velocity zones near the core-mantle boundary from broadband PKP precursors, Science 279(1998) 1701-1703.
[65] Wen, L., P. Solver, D. James and R. Kuehnel, Seismic evidence for a thermo-chemical boundary at the base of the Earth’s mantle, Earth Planet. Sci. Lett. 189(2001) 141-153.
[66] Williams, Q. and E. J. Garnero Seismic evidence for partial melt at the base of Earth’s mantle, Science 273 (1996) 1528-1530.
[67] Williams, Q., J. S. Revenaugh, and E. J. Garnero, A correlation between ultra-low basal velocities in the mantle and hot spots, Science 281 (1998) 546-549.
[68] Wysession, M. E., Large-scale structure at the core-mantle boundary from diffracted waves, Nature 382(1996) 244-248.
[69] Wysession, M. E., A. Langenhorst, M. J. Fouch, K. Fischer, G. I. Al-Eqabi, P. J. Shore, T. J. Clarke, Lateral variations in compressional/shear velocities at the base of the mantle, Science 284(1999) 120-124.
[70] Wysession, M. E., T. Lay, J. Revenaugh, Q. Williams and E. J. Garnero, The D” discontinuity and implications, In *The Core Mantle Boundary*, ed. M. Gurnis, M. E. Wysession, E. Knittle, B. A. Buffett,Washington, DC: AGU(1998) 273-298.