Global Seismic Tomography:
What we really can say and what we make up

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At a recent meeting, someone said that it is necessary to know what are the strong constraints, weak constraints and myths. There are too many myths to discuss them in this brief presentation; it will focus on the "strong constraints". Even though some of the classification may appear subjective, it is based on sound principles. It is also important to remember that tomography provides only a snapshot of the present velocity anomalies. Temporal extrapolations, which lead people to "see" "subducted slabs" in the lower mantle, are made at significant risk. The same is true, to a lesser extent, with respect to attributing the anomalies to thermal or compositional effects.

The observed anomalies in seismic data result from integration of perturbation in structure either along the ray path, for travel times, or volume for splitting of low order normal modes. Perturbation is a smoothing operation and, assuming constant amplitude, the effect of the component of the structure with a wavelength l_1 compared to that of l_2 is equal to the ratio l_1/l_2. Thus long-wavelength components of the structure are much easier to recover than short-wavelength ones. It is difficult to imagine that a narrow vertical structure (plume?) of 100 km width could be mapped using teleseismic observations, since commonly observed phases such as *P, S, PP* or *SS* have rather large incidence angles in the lower mantle. Its image would be significantly widened and the amplitude greatly diminished. In addition to this smoothing effect, there is also the fact that the spectrum of heterogeneity in the upper and lowermost mantle is distinctly "red", i.e. dominated by large wavelength components [*Su and Dziewonski*, 1991; *Su and Dziewonski*, 1992], which may tend to further impair recovery of short-wavelength features.

Therefore, the large-scale features are most easily recovered and most reliable, which is supported by the fact that, for example, most of the recent whole-mantle *S*-velocity models are quite similar [*Gu et al.*, 1998; *Ritsema et al.*, 1999; *Masters et al.*, 2000; *Megnin and Romanowicz*, 2000]. The following text represents a summary of "strong constraints" for several regions of increasing depth.

Lithosphere and Asthenosphere

Credibility of seismic tomography has been to large extent established by the fact that both mantle wave dispersion maps [*Nakanishi and Anderson*, 1983] and models of upper mantle shear velocity anomalies [*Woodhouse and Dziewonski*, 1984] closely matched predictions from surface tectonics [*Nataf and Ricard*, 1996]. There are exceptions to this: the depth to which seismic velocity anomalies persist as a function of age of the oceanic lithosphere (all mantle models cited above) and the strong radial anisotropy in the Central Pacific.

Surface wave observations, particularly when expanded to include relatively short period (down to 35 s) Love and Rayleigh wave data, demand that age-dependent velocities vary to depths as large as 200 km, while the cooling plate model predicts the thickness of about 100 km. This is particularly clear in the V_{SH} model of Ekström and Dziewonski [1998] at a depth, for example, of 150 km, where the velocities monotonically increase from –4% at the East Pacific Rise, to +3% in the Western Pacific. The V_{SV} part of the model shows an added complexity in the Central Pacific with a secondary minimum (about –3%) just southwest of Hawaii. The decomposition of the model into an isotropic (Voigt average) and anisotropic part ($V_{SV} - V_{SH}$) parts clarifies the picture. The isotropic model for the Pacific plate is entirely consistent with the cooling with age (except for the segment between EPR and "Superswell", which is characterized by low velocities and – presumably – higher temperatures at 150 km depth. The anisotropic model, however, is close to zero underneath the EPR, but shows a distinct minimum some 500 km southwest of Hawaii. The anisotropy rapidly decreases between 150 and 250 km depth. The explanation is likely to involve a significant vertical influx of material under the Darwin Rise.

The presence of radial anisotropy has also been reported under the cratons [*Gung et al.*, 2003], and it might be able to explain the long-standing controversy on the depth of the continental roots [*Jordan*, 1975]. Gung *et al.* [2003] suggest that the velocity anomaly associated with cratons ends at about 200-250 km, but is underlain by transversely anisotropic material with $V_{SH} > V_{SV}$.

Transition Zone

It is difficult to think of a more controversial geophysical problem than the flow of the mantle material across the boundary between the upper and lower mantle. However, there is now good evidence for strong impedance to flow across this boundary. It is based, in part, on the estimates of the patterns of large-scale velocity anomalies above and below the 650 km discontinuity. Gu *et al.* [1998] show that it is possible to satisfy a large and diverse set of travel time data with a model that has distinctly different spectral characteristics above and below the 650 km discontinuity. Even when the continuity is imposed, the radial correlation function [*Jordan et al.*, 1993] shows that the velocity anomalies 100 km below and above the 650 km discontinuity are fully de-correlated, indicating a very steep gradient in the pattern of heterogeneity.

Additional information comes from studies of the topography of the 410 and 660 km discontinuities, using *SS* - *SdS* differential precursor times [*Shearer and Masters*, 1992; *Gu et al.*, 1998]. Simultaneous inversion for mantle shear velocity and topography of the transition zone discontinuities shows very little large wavelength topography on the 410 km discontinuity and much larger relief on the 650 km discontinuity [*Gu et al.*, 2003]. Also, the shape of the two surfaces is de-correlated [*Gu et al.*, 1998]. However, the 650 km discontinuity topography is highly correlated with the velocity anomalies in the transition zone. A simple, although not unique, interpretation is that the negatively buoyant slabs pond in the transition zone.

A shortcoming of seismic tomography is that it provides only a snapshot of the heterogeneity; attempts to extrapolate it in time are uncertain. But the ponding of slabs and - judging from volume of the anomalies - a substantial residence time, does indicate the possibility that this material could be, at least in part, re-circulated in the upper mantle; not unlike the megalith proposed by Ringwood and Irifune [1988].

Middle Mantle

Whether or not one accepts the result of Gu *et al.* [2001], there is general agreement that, at least, *S*-wave velocity models show a distinctly different spectrum in the middle mantle (from 650 km to about 2500 km); the power spectrum is nearly flat as a function of harmonic degree and, generally, much weaker than in the upper mantle. Tackley *et al.* [1994] obtained such a change in spectral characteristic in their numerical simulation of mantle convection, in which there is discontinuity in flow across the 650 discontinuity caused by an endothermic phase transformation. There may be, of course, other causes of such a disruption of flow, but the spectral effect is eerily similar.

In many papers there have been suggestions of additional discontinuities in the lower mantle. It appears that on the global scale there is not such discontinuity with a specific radius. Even a discontinuity with a several hundred kilometers of topography and 0.5% velocity change is highly unlikely, judging from the behavior of slowness (*dT/dD) of P*- and *S*-waves as a function of distance*,* which change between 35^o and 90^o in a remarkably linear fashion [*Dziewonski et al.*, 1993]. Gu *et al.* [2001] experimented with allowing an abrupt change of heterogeneity pattern across 1000 km [*Kawakatsu and Niu*, 1994; *Fukao et al.*, 2001] and 1800 km [*van der Hilst and Karason*, 1999]; in neither case there has been a change in the pattern of the power spectra. It appears therefore, that the middle mantle has a relatively low level of heterogeneity, distributed rather evenly among the spherical harmonics up to degree 20. This does not mean that there could not be local discontinuities, although local perturbations in the gradient may cause caustics giving an appearance of a discontinuity [*Tromp and Dziewonski*, 1998].

The middle mantle is where it is widely believed that the coherent images of subducted slabs are visible. Of these, perhaps the most famous is the “Farralon slab” [*Grand et al.*, 1997; *van der Hilst and Karason*, 1999], which seems to penetrate lower mantle from the 650 km discontinuity to the core-mantle boundary in both *P*- and *S*-velocity models. However, models derived with a greater variety of data types and, consequently, more even volume sampling show large-scale high velocity features in places where there was no subduction in the past 200 Ma, do not show it in places where subduction took place and in the case of the South Sandwich Island the “slab” occupies a volume that is completely out of proportion in comparison with the duration and rate of subduction in this region [*Bijwaard et al.*, 1998]. While it is likely that there is some link between the upper and lower mantle flow, the nature of this link is not clear. Recently, Pysklywec *et al.* [2003] proposed that the dynamics in the Fiji-Tonga-Vanuatu region during the last 10 Ma might have been caused by an avalanche of the ponded slab material under the southern part of the region. In terms of seismic tomography, the region is characterized by relatively normal velocities in the transition zone, but a large volume of faster than average mantle between 650 and 1100-1200 km depth. In their model, the process is still ongoing and may present a unique opportunity of monitoring an “avalanche” in progress.

Lowermost Mantle and Core-Mantle Boundary

It has been discovered a fairly long time ago that the level of heterogeneity increases near the core-mantle boundary (CMB) [*Julian and Sengupta*, 1973; *Dziewonski et al.*, 1977]. This increase may be present at all wavelengths, but it is very clear at the gravest harmonics: degrees 2 and 3 [*Dziewonski*, 1984], which strongly dominate global maps at some 150 km above the CMB. The geometry of these ultra-long anomalies is very similar to the corresponding harmonics in the geoid field, but have the opposite sign [*Dziewonski et al.*, 1977]; the fact that led to hypothesis that then density variations are proportional to velocity variations; the sign of the proportionality coefficient positive if dynamic deformation of boundaries is taken into account [*Hager et al.*, 1985]; this would be consistent with a thermal rather than compositional origin of the anomalies. There is an overall agreement between the predicted [*Hager et al.*, 1985] and observed [*Morelli and Dziewonski*, 1987] topography of the CMB [*Dziewonski et al.*, 1993].

The geometry of the large-scale velocity anomalies is simple and bears a relationship to the surface tectonics. The higher than average velocities are arranged in a ring circumscribing the Pacific basin, with a slight landward shift, thus potentially reflecting accumulation of the subducted material. There are two main low velocity regions, sometimes called superplumes [*Romanowicz and Gung*, 2002]: one under Africa (Great African Plume) [*Dziewonski et al.*, 1993] and the other one under Pacific (Equatorial Pacific Plume Group), [*Dziewonski et al.*, 1993]. Nearly all hotspots (over 90%) can be found over lower than normal velocities in model V3.I of Morelli and Dziewonski [1986; 1991].

The velocity anomalies extend significantly from the CMB into the middle mantle and perhaps reach the 650 km discontinuity; thus, they are continuous across the so-called D'' region. *Romanowicz and Gung,* [2002] propose that the effects of superplumes extend into the upper mantle; they point out toward good correlation of degree-2 velocity anomalies near the CMB and *Q* anomalies in the transition zone, with perhaps, only the thermal coupling across the 650 km discontinuity.

Recently, the Princeton group [*Montelli et al.*, 2003b; *Montelli et al.*, 2003a] derived a *P*-velocity model in which some of the hotspots continue from surface well into the lower mantle and perhaps all the way to the CMB. It is difficult to assess the validity of this claim before publication, but a degree of skepticism is justified in view of discussion in the introductory part of this extended abstract and the fact that the authors seem not to recover well the dominant large-wavelength of the anomaly field in the lowermost mantle.

There are many other smaller-scale (regional) anomalies near the CMB. Among them are anisotropy; smaller scale, rather abrupt changes in the sign of the anomalies; 10-30 km thin ultra-low velocity zones at the base of the mantle [*Garnero et al.*, 1993], which seem to be preferentially located within the large-scale low velocity anomalies. Their relation to the surface tectonics is unclear.

References

Bijwaard, H., W. Spakman, and E.R. Engdahl, Closing the gap between regional and global travel time tomography, *J. Geophys. Res.*, *103* (B12), 30055-30078, 1998.

Dziewonski, A.M., Mapping the lower mantle: Determination of lateral heterogeneity in P velocity up to degree and order 6, *J. Geophys. Res.*, *89* (B7), 5929-5952, 1984.

Dziewonski, A.M., A.M. Forte, W.-J. Su, and R.L. Woodward, Seismic tomography and geodynamics, in *Relating Geophysical Structures and Processes: The Jeffreys Volume*, edited by K. Aki, and R. Dmowska, pp. 67-105, AGU, Washington, D. C., 1993.

Dziewonski, A.M., B.H. Hager, and R.J. O'Connell, Large-scale heterogeneities in the lower mantle, *J. Geophys. Res.*, *82* (B2), 239-255, 1977.

Ekström, G.A., and A.M. Dziewonski, The unique anisotropy of the Pacific upper mantle, *Nature*, *394* (6689), 168-172, 1998.

Fukao, Y., S. Widiantoro, and M. Obayashi, Stagnant slabs in the upper and lower mantle transition region, *Rev. Geophys.*, *39* (3), 291-323, 2001.

Garnero, E.J., S.P. Grand, and D.V. Helmberger, Low *P*-wave velocity at the base of the mantle, *Geophys. Res. Lett.*, *20*, 1843-1846, 1993.

Grand, S.P., R.D. van der Hilst, and S. Widiyantoro, Global seismic tomography: A snapshot of convection in the Earth, *GSA Today*, *7*, 1-7, 1997.

Gu, Y., A. Dziewonski, and C.B. Agee, Global de-correlation of the topography of transition zone discontinuities, *Earth Planet. Sci. Lett.*, *157* (1-2), 57-67, 1998.

Gu, Y., A. Dziewonski, W. Su, and G. Ekstrom, Models of the mantle shear velocity and discontinuities in the pattern of lateral heterogeneities, *J. Geophys. Res.*, *106* (B6), 11169-11199, 2001.

Gu, Y.J., A.M. Dziewonski, and G. Ekstrom, Simultaneous inversion for mantle shear velocity and the topography of transition zone discontinuities, *Geophys. J. Int.*, *in press*, 2003.

Gung, Y., M. Panning, and B. Romanowicz, Global anisotropy and the thickness of continents, *Nature*, *422*, 707-711, 2003.

Hager, B.W., R.W. Clayton, M.A. Richards, R.P. Comer, and A. Dziewonski, Lower mantle heterogeneity, dynamic topography and the geoid, *Nature*, *313* (6003), 541-545, 1985.

Jordan, T.H., The continental tectosphere, *Reviews of Geophysics and Space Physics*, *13*, 1-13, 1975.

Jordan, T.H., P. Puster, G.A. Glatzmier, and P.J. Tackley, Comparisons between seismic Earth structures and mantle flow models based on radial correlation functions, *Science*, *261* (5127), 1427-1431, 1993.

Julian, B.R., and M.K. Sengupta, Seismic travel time evidence for lateral inhomogeneity in the deep mantle, *Nature*, *242* (5398), 443-447, 1973.

Kawakatsu, H., and F.-L. Niu, Seismic evidence foe a 920-km discontinuity in the mantle, *Nature*, *371*, 301-305, 1994.

Masters, G., S. Johnson, G. Laske, and H. Bolton, A shear velocity model of the mantle, *Phil. Trans. R. Soc. Lond.*, *A354*, 1385-1411, 2000.

Megnin, C., and B. Romanowicz, The 3D velocity structure of the mantle from the inversion of body, surface, and higher mode waveforms, *Geophys. J. Int.*, *143* (3), 709-728, 2000.

Montelli, R., G. Nolet, G. Masters, F.A. Dahlen, and S.-H. Hung, Finite frequency tomography reveals a variety of plumes in the mantle, in *Plume IV: Beyond the Plume Hypothesis*, Hverageerdi, Iceland, 2003a.

Montelli, R., G. Nolet, G. Masters, F.A. Dahlen, and S.-H. Hung, Global *P* and *PP* traveltime tomography: Rays versus waves, *Geophys. J. Int.*, *(submitted)*, 2003b.

Morelli, A., and A.M. Dziewonski, 3D structure of the Earth's core inferred from travel time residuals, *EOS, Trans. AGU*, *67*, 311, 1986.

Morelli, A., and A.M. Dziewonski, Topography of the core-mantle boundary and lateral homogeneity of the liquid core, *Nature*, *325* (6106), 678-683, 1987.

Morelli, A., and A.M. Dziewonski, Joint determination of lateral heterogeneity and earthquake location, in *Glacial Isostasy, Sea-Level and Mantle Rheology*, edited by R. Sabadini, K. Lambeck, and E. Boschi, pp. 515-534, NATO, 1991.

Nakanishi, I., and D.L. Anderson, Measurements of mantle wave velocities and inversion for lateral heterogeneity and anisotropy; 1, Analysis of great circle phase velocities, *J. Geophys. Res.*, *88* (B12), 10267-10283, 1983.

Nataf, H.-C., and Y. Ricard, 3SMAC; an a priori tomographic model of the upper mantle based on geophysical modeling, *Phys. Earth Planet. Int.*, *95* (1-2), 101-122, 1996.

Pysklywec , R.N., J.X. Mitrovica, and M. Ishii, Mantle avalanche as a driving force for tectonic reorganization in the Southwest Pacific, *Earth Planet. Sci. Lett.*, *209* (1-2), 29-38, 2003.

Ringwood, A.E., and T. Irifune, Nature of the 650-km seismic discontinuity – implications for mantle dynamics and differentiation, *Nature*, *331*, 131-136, 1988.

Ritsema, J., H.J. van Heijst, and J.H. Woodhouse, Complex shear wave velocity structure imaged beneath Africa and Iceland, *Science*, *286*, 1925-1928, 1999.

Romanowicz, B., and Y. Gung, Superplumes from the core-mantle boundary to the lithosphere; implications for heat flux, *Science*, *296* (5567), 513-516, 2002.

Shearer, P.M., and T.G. Masters, Global mapping of topography on the 660-km discontinuity, *Nature*, *355* (6363), 791-796, 1992.

Su, W.-J., and A. Dziewonski, Predominance of long-wavelength heterogeneity in the mantle, *Nature*, *352* (6331), 121-126, 1991.

Su, W.-j., and A. Dziewonski, On the scale of mantle heterogeneity, *Phys. Earth Planet. Int.*, *74* (1-2), 29-54, 1992.

Tackley, P.J., D.J. Stevenson, G.A. Glatzmaier, and G. Schubert, Effects of multiple phase transitions in a three-dimensional spherical model of convection in Earth's mantle, *J. Geophys. Res.*, *99* (B8), 15877-15901, 1994.

Tromp, J., and A. Dziewonski, Two views of the deep mantle, *Science*, *281* (5377), 655-656, 1998.

van der Hilst, R.D., and H. Karason, Compositional heterogeneity in the bottom 1000 kilometers of Earth's mantle: Toward a hybrid convection model, *Science*, *283* (1885-1887), 578-584, 1999.

Woodhouse, J.H., and A.M. Dziewonski, Mapping the upper mantle; three-dimensional modeling of Earth structure by inversion of seismic waveforms, *J. Geophys. Res.*, *89* (B7), 5953-5986,, 1984.