GEOPHYSICAL RESEARCH LETTER, VOL. 20, NO. 7, PAGES 631-634, APRIL 9, 1993

# Degrees 2, 4, 6 Inferred from Seismic Tomography

JEAN-PAUL MONTAGNER

*Seismological Laboratory, Institut de Physique du Globe, Paris, France*

BARBARA ROMANOWICZ

*Seismographic Station, University of California, Berkeley, California, U.S.A.*

**Lateral heterogneities of geophysical fields (gravity, magnetic, seismic velocities...) are usually expended into spherical harmonics. Free oscillation and geoid data show that heterogeneity in the deep Earth's mantle is dominated by degree 2. However, its geographical pattern and its location at depth is still questionable. Recent tomographic models of seismic velocity, anisotropy and anelasticity obtained from GEOSCOPE and GDSN data, make it possible to gain more insight on this problem. They show that at depth larger than 400km ± 100km, the degree 2 and t a less extent, the degree 6 arise as the most important features. These new models also display a large degree 4 for radial anisotropy at large depths. A simple flow pattern can explain the predominance of these different degrees 2, 4, 6 and it is shown that degrees 2, 4, 6 in the transition zone are not independent. They are compared to the corresponding degrees of the hotspot distribution and geoid. A possible relation between the degree 2 of velocity and the degree 4 of radial anisotropy is also displayed. However, the different location of degree 2 in the upper mantle and the lower mantle is still puzzling.**

## 1. INTRODUCTION

In order to compare different geophysical parameters, it is usual to expand them into spherical harmonics $Y_l^m$ where l is the angular order and m the azimuthal order. Each degree is also characterized by its power spectrum $P_l$ related to the amplitude of anomalies. Degree 2 ($l = 2$) is the most important lateral deviation with respect to a laterally homogeneous sphere. In Seismology, the importance of degree 2 was demonstrated from the location of poles of long period normal mode eigenfrequencies [*Masters et al.*, 1982]. The geoid also presents a large degree 2 [*Lerch et al.*, 1983] which has been so far attributed to deep-seated anomalies in the lower mantle. However, the origin at depth is still controversial. *Masters et al.* [1982] prefer it to be located in the transition zone between 400 and 660km. *Romanowicz et al.* [1987], display a maximum in degree 2 in the depth range 200-400km. On the other hand, *Kawakatsu* [1983] sees the degree 2 as a consequence of surface tectonics. However, these observations from normal modes only provide information on even degrees and it was necessary to wait for the first global tomographic models [*Woodhouse and Dziewonski*, 1984; *Nataf et al.*, 1986] to be able to compare even degrees to odd degrees. It turns out that degree 2 becomes predominant in the upper mantle (in the transition zone for *Woodhouse and Dziewonski* [1984], at shallower depth for other models (see *Romanowicz* [1991]). This contrasts with more surficial parameters such as plate velocities which display a regular decrease of power with angular order (see for example, *Hager and O'Connell*, 1979).

More recent tomographic models of the upper mantle [*Woodhouse and Dziewonski*, 1989; *Montagner and Tanimoto*, 1991, hereafter referred as MT; *Romanowicz*, 1990; *Roult et al.*, 1990] confirm the importance of degree 2 in the transition zone but new observations can be made: Degree 6 appears to be an important degree at long period [T>200s; *Montagner and Tanimoto*, 1990] and at large depths [*MT*]. The model AUM (anisotropic upper mantle model) of MT gives both the $V_{SV}$-model and the radial anisotropy ($\xi = \frac{V_{SH}-V_{SV}}{V_{SV}}$). Figure 1 presents the power spectra of $\xi$ for AUM. It must be noted that the spherical harmonic expansion of $\xi$, shows that degrees 4 (and 5) become predominant below 300km. The same result arises if we consider the models of *Nataf et al.* [1986] and of *Roult et al.* [1990] (though only even angular order distributions are available for this model).

Therefore, these different observations make it possible to address some general and basic questions: What is the origin at depth of degree 2, of degree 6? Is there any relationship between degree 2 and degree 6? in the upper mantle? in the lower mantle? How can we explain the predominance of degree 4 (and 5) for radial anisotropy? In this paper, we show how to relate the degree 2 of seismic velocities with degree 6 of velocities on one hand and hotspot distribution and with degree 4 of radial anisotropy on the other hand. In order to illustrate our discussion, we will consider two recent tomographic models, the model AUM of MT and the model MDLSH of *Tanimoto* [1990] for the whole mantle.

## 2. A SIMPLE FLOW MODEL

Let us consider a very simple flow pattern with two upgoing and two downgoing flows along the equator (figure 2a). Upgoing flow is associated with arbitrary slow velocities (-10%) and downgoing flow with high velocities (+10%). The width of plumes is about 20 degrees. This simple model is not meant at this stage, to represent any realistic convection model but to illustrate some predictions from such a simple pattern. When a spherical harmonics expansion is performed on this simple velocity distribution, a large degree 2 is naturally found, but, more surprisingly the second most important degree is degree 6 (figure 2b). This relative predominance of degree 6 with respect to degree 4 does not depend on the shape (width and amplitude) of the upgoing and downgoing flows, which only affects the decreasing slope of the power spectrum with angular order. A physical understanding of that statement [*Bercovici et al.*, 1991] stems from the fact that a degree 6 flow pattern can present upgoing and downgoing flows exactly at the same place as those of degree 2; such is not the case for degree 4.



Paper number 92GL01204
0094-8534/93/92GL-01204$03.00

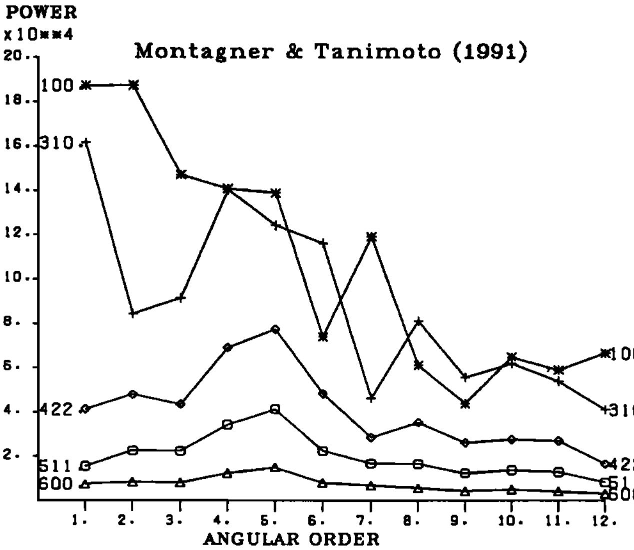


Fig. 1. Power spectrum of radial anisotropy $\xi$ [*Montagner and Tanimoto*, 1991].

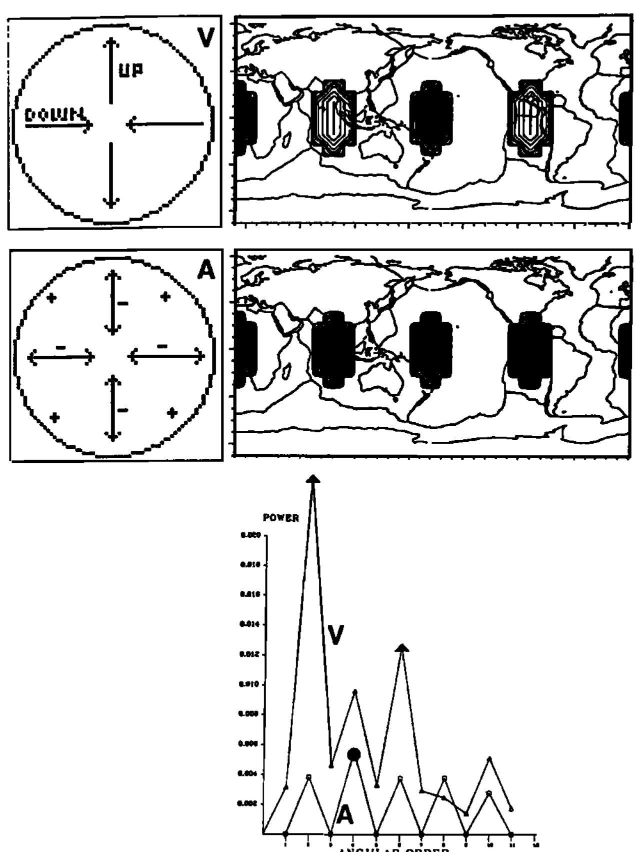


Fig. 2. A simple degree 2 flow pattern.
Left: Equatorial cross-sections (top $V_{SV}$, middle $\xi$). Arrows indicate the sense of flow of matter.
Right: corresponding horizontal maps of $V_{SV}$ velocity and radial anisotropy $\xi$ distributions.
Bottom: $V_{SV}$ (V) and $\xi$ (A) power spectra of these anomalies.

Now, one can infer the distribution of radial anisotropy $\xi = \frac{V_{SH}-V_{SV}}{V_{SV}}$ for this flow pattern. For anisotropy, it does not matter much whether the flow is upgoing or downgoing but it is only important to know whether it is vertical or horizontal. When the flow is vertical, $\xi$ is negative, and when horizontal, $\xi$ is positive [*Anderson and Regan*, 1983]. Therefore, one can reasonably assume that 4 zones of negative radial anisotropy can be associated with this simple convection pattern (figure 2a). The corresponding spherical harmonics expansion displays a large degree 4 as expected (figure 2b).

Therefore, this simple flow pattern induces large degrees 2 and 6 for seismic velocities and a large degree 4 for radial anisotropy. Thus, we are able to understand the relative amplitude of different degrees of the spherical harmonics expansion of velocity and radial anisotropy. However, the phase at the surface of the Earth of the corresponding distributions must be coherent i.e. the anomalies have to be located at the right places with respect to each other. We will see if such is the case for the Earth's mantle.

## 3. PATTERN OF DEGREE 2, 4, 6

The degree 2 pattern for AUM and MDLSH of *Tanimoto*, [1990] has been compared to the degree 2 of the hotspot distribution [*Richards and Hager*, 1988], quite similar to the degree 2 of geoid (figure 3a-f). As depth increases, the degree 2 pattern changes. At shallow depths (200km), the degree 2 presents slow velocities near equator and high velocities at poles (zonal pattern). At depths larger than 400km, anomalies associated with degree 2 are located along the equator. High velocities are correlated with slabs below Eastern Asia and South America, and slow velocities with the East Africa-Central Indian ridge and with the Central Pacific Ocean. An interesting feature arises, clearly visible on the East- West cross-section along Equator (figure 3e). As depth increases, degree 2 anomalies are progressively offset westwards. This point will be discussed later on.

For the degree 4 of radial anisotropy, we have only plotted $\xi$ at 470km of depth (figure 4). The degree 4 distribution is sectorial along the equator with a succession of north-south positive and negative anomalies, which makes it compatible with a degree 2 pattern according to our prediction, as presented in section 2. Therefore, radial anisotropy is in agreement with a simple degree 2 pattern below 400km. However, let us note that degree 4 is slightly offset westwards, which means either that the location is inaccurate or that the thermal anomaly does not necessarily coincide with the maximum in the strain field.

Maps for degree 6 of $V_{SV}$ velocity are plotted on figures 5 for the same depths as those of degree 2 and compared to degree 6 of the hotspot distribution. As a matter of fact, according to a selection of 47 hotspots [*Richards and Hager*, 1988], degree 6 shows up as a secondary peak. When plotted, the degree 6 of hotspot distribution and seismic velocities around a depth of 400km [*Woodhouse and Dziewonski*, 1984] presents the same pattern with two antipodal extrema in East Africa and in French Polynesia [*Cazenave et al.*, 1989]. We can check this point in figure 5b and the correlation of degree 6 of $V_{SV}$ velocity and degree 6 of hotspots is fairly good ($\rho = 0.45$ for AUM and $\rho = 0.69$ for MDLSH above the 90% confidence level). At a depth of 470km, the correlation between degrees 6 of $V_{SV}$ and hotspot distribution is still very good. But from MDLSH, it rapidly degrades in the depth range 660-1150km. It means that if degree 6 is actually representative of the hotspots, they can be traced down almost in the whole upper mantle but not below 1000km.

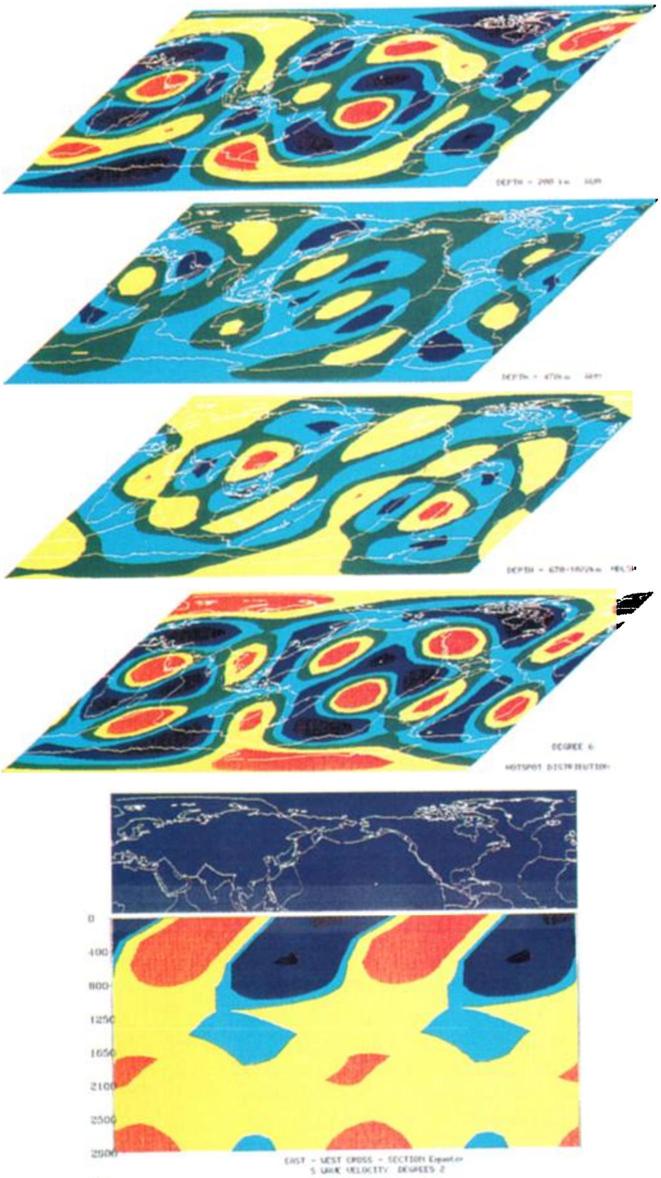

Fig. 3. Degree 2 maps. From top to bottom: a) 200km (AUM), b) 470km (AUM), c) 850km (MDLSH), d) Hotspot.
Fig. 3*e*. Vertical cross-section along Equator of MDLSH.

Fig. 4. Degree 4 map at 470km of depth (AUM).

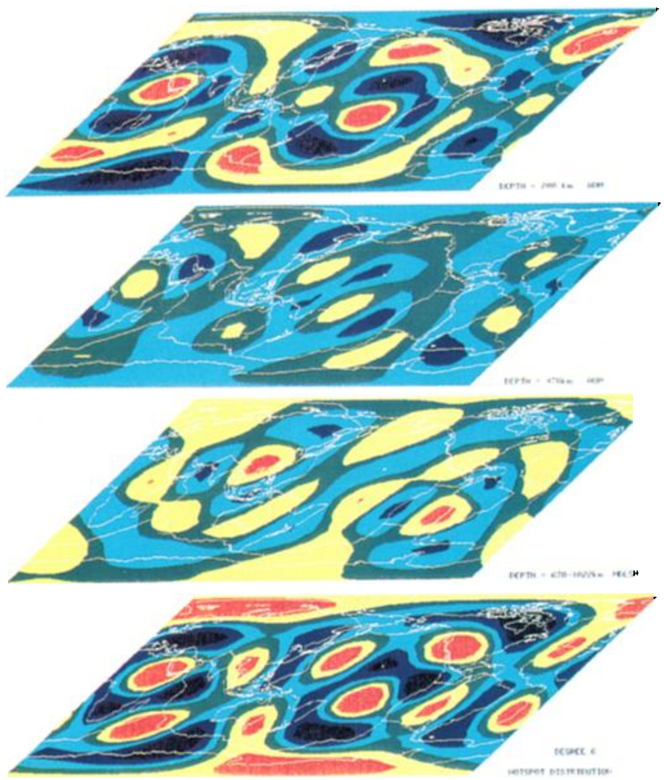

Fig. 5. Degree 6 maps for the same depths as for degree 2 (fig. 3).

## 4. DISCUSSION

The simple model of convection with two upgoing and two downgoing flows qualitatively explains the power spectrum of $V_{SV}$ and radial anisotropy $\xi$ heterogeneities in the deep upper mantle. However, the location at different depths of the main degrees displays additional complexity. Vertical cross-section along Equator (figure 3e) shows that degree 2 is offset westwards as depth increases. Three tentative explanations can be proposed. The first simple idea consists in attributing this offset to the Coriolis force acting on the flow. It has the right sense and the same dipping effect on upgoing and downgoing flows. However, the nondimensional number associated with this force, the Ekman number is so large ($10^{14}$)[*Richter*, 1973] that the Coriolis force can be always neglected. A second explanation can be found in some counterbalancing effect of the net rotation of the lithosphere [*Minster and Jordan*, 1974]. *Ricard et al.* [1991] have shown that lateral variations of viscosity can induce this net rotation. One can imagine that lateral viscosity heterogeneity varying with depth will induce differential drift with velocity varying with depth. The third explanation stems from the anelastic nature of the upper mantle. According to *Romanowicz* [1990] the quality factor Q also displays a degree 2 pattern which is shifted westwards with respect to velocity degree 2, and dispersion effects will tend to align it with that of the geoid. This has been confirmed by recent work of *Suda et al.* [1991]. Lateral variations in viscosity associated with the lateral variations in Q would have a similar effect through the introduction of lateral variations in the velocity-density relations.

As mentioned previously, the distribution of degree 4 for radial anisotropy is in agreement with a prediction from degree 2. It must be noted that below 400km [*Montagner and Anderson*, 1989], the average radial anisotropy is very small but the degree 4 of $\xi$ derived in AUM is not induced by a trade-off with $V_{SV}$ because in that case, the power spectrum of $\xi$ should present the same degree 2 pattern as $V_{SV}$. Radial anisotropy presents the same sectorial pattern as degree 2 though slightly offset with respect to a prediction from degree 2.

The degree 6 of hotspots is well correlated with degree

6 of $V_{SV}$ velocity in the whole upper mantle. Therefore if degree 6 is effectively characteristic of hotspots, this means that, despite their small size, we are able to detect them through their long wavelength signature. This correlation was previously displayed by *Cazenave et al.* [1989] from the tomographic model M84C of *Woodhouse and Dziewonski* [1984]. However, this degree 6 is not compatible with the geoid degree 2 (according to the prediction of section 2) but in agreement with the degree 2 at the base of the upper mantle. Moreover, the correlation between degree 6 of hotspots and seismic degree 6 is good in the whole upper mantle, but dramatically decreases between 600 and 1000km and is very poor in the lower mantle. This loss of correlation around 660km is confirmed by more recent models derived from body waves [*Su and Dziewonski*, 1991]. From seismic tomography, one can trace the hotspot degree 6 down to the transition zone but not in the lower mantle. Therefore, according to our results, hotspots do not necessarily originate at the core-mantle boundary but might originate in the transition zone.

*Acknowledgments.* We are grateful to Claude Allegre, Anny Cazenave and Annie Souriau for fruitful discussions, Henri-Claude Nataf and Brian Kennett for their constructive reviews. Seismological Laboratory, Institut de Physique du Globe, Paris, Contribution IPG 1233. Contribution ASP TOMOGRAPHIE.

## REFERENCES

Anderson, D.L., and J. Regan, Upper mantle anisotropy and the oceanic lithosphere, *Geophys. Res. Lett.*, *10*, 841–844, 1983.

Bercovici, D., G. Schubert, and G.A. Glatzmaier, Modal growth and coupling in three-dimensional spherical convection (abstract), IUGG meeting, Vienna, August 1991.

Cazenave, A., A. Souriau, and K. Dominh, Global coupling of Earth surface topography with hotspots geoid and mantle heterogeneities, *Nature*, *340*, 54–57, 1989.

Hager, B., and R. O'Connell, Kinematic models of large-scale flow in the Earth's mantle, *J. Geophys. Res.*, *84*, 1031–1048, 1979.

Kawakatsu, H., Can 'Pure-Path' models explain free oscillation data?, *Geophys. Res. Lett.*, *10*, 186–189, 1983.

Lerch, F.J., S.M. Klosko, R.E. Laubscher, and C.A. Wagner, Gravity improvement using GEOS3 (GEM9 and 10), *J. Geophys. Res.*, *84* 3897–3916, 1979.

Masters, G., T.H. Jordan, P.G. Silver, and F. Gilbert, Aspherical earth structure from fundamental spheroidal- mode data, *Nature*, *298*, 609–613, 1982.

Montagner, J.P., and D.L. Anderson, Constrained reference mantle model, *Phys. Earth Planet. Int.*, *58*, 205–227, 1989.

Montagner J.P., and T. Tanimoto, Global anisotropy in the upper mantle inferred from the regionalization of the phase velocities, *J. Geophys. Res.*, *95*, 4797–4819, 1990.

Montagner J.P., and T. Tanimoto, Global upper mantle tomography of seismic velocities and anisotropies, *J. Geophys. Res.*, In Press, 1991.

Nataf, H.C., I. Nakanishi, and D.L. Anderson, Measurements of mantle wave velocities and inversion for lateral heterogeneities and anisotropy. Part III: Inversion, *J. Geophys. Res.*, *91*, 7261–7307, 1986.

Ricard, Y., C. Doglioni, and R. Sabadini, Differential rotation between lithosphere and mantle: A consequence of lateral mantle viscosity variations, *J. Geophys. Res.*, *96*, 8407- 8415, 1991.

Richards, M.A., and B.H. Hager, The Earth's Geoid and the Large-scale structure of Mantle Convection, in *The Physics of the Planets*, Edited by S.K. Runcorn, pp. 247-271, John Wiley, New-York, 1988.

Richter, F.M., Convection and the large-scale circulation of the mantle, *J. Geophys. Res.*, *78*, 8735–8745, 1973.

Romanowicz, B., The upper mantle degree 2: constraints and inferences on attenuation tomography from global mantle wave measurements, *J. Geophys. Res.*, *95*, 11,051–11,071, 1990.

Romanowicz, B., Seismic Tomography of the Earth's mantle, *Ann. Rev. Earth Planet. Sci.*, *19*, 77–99, 1991.

Roult, G., B. Romanowicz, and J.P. Montagner, 3D upper mantle shear velocity and attenuation from fundamental mode free oscillation data, *Geophys. J. Int.*, *101*, 61–80, 1990.

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

Suda, N., N. Shibata, and Y. Fukao, Degree-2 pattern of attenuation structure in the upper mantle from apparent complex frequency measurements of fundamental spheroidal modes, *Geophys. Res. Lett.*, *18*, 1119–112, 1991.

Tanimoto, T., Long wavelength S-wave velocity Structure throughout the mantle, *Geophys. J. Int.*, *100*, 327–336, 1990.

Woodhouse, J.H., and A.M. Dziewonski, Mapping the upper mantle: Three dimensional modelling of Earth structure by inversion of seismic waveform, *J. Geophys. Res.*, *89*, 5953–5986, 1984.

Woodhouse, J.H., and A.M. Dziewonski, Seismic modelling of the Earth's large-scale three- dimensional structure, *Phil. Trans. R. Soc. Lond.*, *A328*, 291–308, 1989.

J.P. Montagner, Seismological Laboratory, Institut de Physique du Globe, 4 Place Jussieu, 75252 Paris, France.

B. Romanowicz, Seismographic Station, Earth Sciences Bldg 475, U.C. Berkeley CA 94720, U.S.A.

(Received December 5, 1991;
Revised May 25, 1992;
Accepted May 25, 1992)