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Seismically "fast" geodynamic mantle models

J. Huw Davies
Dept of Earth Sciences, University of Liverpool

Hans-Peter Bunge
Dept of Geosciences, Princeton University

Abstract. We show that biased sampling of Earth structure by body-waves provides an additional explanation for the fact that short period body-wave seismic velocity models are faster than long-period free-oscillation models (apparent dispersion). We do this by tracing a set of body-waves used in global tomography studies through synthetic seismic models derived from mantle circulation models. The histograms of the arrival time residuals have a negative mean for all the models investigated. We interpret that this results from a predominance of rays sampling the fast structures of subduction zones due to the concentration of sources there. The interpretation successfully passes two tests; the first showed that the signal is tectonically controlled, while the second involved breaking the correlation between ray paths and structures when no bias is found. The negative mean implies that Earth as sampled by body-waves is fast compared to an average reference Earth (e.g. as measured from free-oscillations). This effect (and others) will need to be quantified before attenuation can be extracted from the apparent dispersion.

1. The discrepancy between body-wave and free oscillation models

S-wave travel times predicted on the basis of the 1066B normal mode based model [*Gilbert & Dziewonski*, 1975] are on average 4.3s larger than those of the body-waves of *Hales & Roberts* [1970], while P-waves were 1.6s larger. *Nolet & Moser*, [1993] summarize much of the data and suggest that the discrepancy for S-waves between body-wave and normal mode models is of order 4s. One can expect a somewhat smaller discrepancy between the observed P-body-wave travel times and the predicted travel times through normal-mode models. Explanations for the difference have included dispersion due to attenuation [*Jeffreys*, 1965; *Liu et al.*, 1976], a bias towards continental regions in observed traveltimes of S, a bias caused by ray bending (and diffraction) around low-velocity regions [*Nolet & Moser*, 1993], and the iterative process used to infer both earthquake origin times and travel times from measured arrival times [*Dahlen & Tromp*, 1998].

Here we introduce a further possible explanation by suggesting that it has a contribution from the uneven ray sampling of the mantle. We study this possibility by tracing a set of rays, previously used in body-wave tomography, through a suite of mantle circulation models (MCMs) and evaluating the residuals. Significantly we find that all the histograms of the residuals have a non-zero mean, biased towards a "fast" Earth. This suggests that a part of the discrepancy can result from the preferential sampling of fast subducting slabs by the inhomogeneous distribution of rays resulting from the location of many earthquakes in subduction zones.

2. Input mantle circulation models

We study the effect of inhomogeneous ray sampling on ray travel time residuals in six mantle circulation models (MCMs) [*Bunge et al.*, 1998] constrained by the history of Cenozoic and Mesozoic plate motions [*Lithgow-Bertelloni & Richards*, 1998]. For simplicity, all MCMs are assumed to have uniform chemical composition, with the viscosity increasing in the lithosphere by a factor of 100 relative to the upper mantle. The Reference MCM (MODEL 1) is heated purely from within by radioactivity, and the lower mantle viscosity increases by a factor of 40 relative to the upper mantle, as suggested by studies of the geoid [*Hager & Richards*, 1989] and post-glacial rebound [*Mitrovica*, 1996]. We then proceed by adding the anomalous buoyancy effects from mantle phase transitions in MODEL 2, or 25 % bottom heating from the core (MODEL 3), or the effects from stiffening the lower mantle by increasing the viscosity jump in the transition zone (factor 100) in MODEL 4. We also include 2 hybrid models, which combine bottom heating with the effects of phase transitions (MODEL 5) or a high viscosity lower mantle (MODEL 6). These 6 models effectively span a large part of parameter space. If the bias is found in all 6 models, it would confirm the robustness of our finding. Parameter values for all 6 MCMs are listed in Table 1. We convert the MCMs into seismic models by assuming that all velocity anomalies in the mantle are of a thermal origin. This is probably a good first order assumption since chemical and phase heterogeneity will

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Table 1. Details of mantle circulation models

MODEL	Core Heating	γ	$\eta(l)/\eta(u)$	mean
1	0%	0,0	40	-0.54
2	0%	+2,-3	40	-0.78
3	0%	0,0	100	-0.62
4	25%	0,0	40	-0.88
5	12%	+2,-3	40	-0.81
6	25%	0,0	100	-0.81

γ, Clapeyron slope of the 410 and 660km discontinuity respectively (MPa/K); $\eta(l)/\eta(u)$, ratio of the lower to upper mantle viscosity; mean, mean of respective histogram (s)

likely play only a minor role in the bulk of the mantle, except near the boundary layers and mantle phase transitions, where they may play a more significant role. Where this assumption breaks down the simple conversion will not apply. The conversion is done by evaluating the lateral thermal *perturbations* away from the average temperatures, and then converting these into slowness (inverse velocity) *perturbations*, for simplicity, by multiplying by a constant 2.5 $\times 10^{-6}$ s/km/K (c.f. $\approx 1.2 \pm 1.2 \times 10^{-6}$ s/km/K from *Duffy & Ahrens* [1992]; $\approx 8 \times 10^{-6}$ s/km/K for olivine at room temperature and pressure; and $\approx 4 \times 10^{-6}$ s/km/K estimated by *Karato [1993]* for the lower mantle). The fact that we convert only the thermal perturbation to a seismic perturbation and not the absolute temperature to an absolute velocity is significant. This implies that the 3D model is independent of the actual radial model; i.e. the synthetic residuals are independent of the reference model. The underlying 1D reference model can be considered an 'average' model derived from normal-mode data, which by their very nature average the lateral heterogeneity. Implicitly we are assuming that the radial model is perfect. For the ray tracing we use iasp91 [*Kennett & Engdahl*, 1991] as the seismic velocity model. We use the event locations of *Engdahl et al.* [1998], and a ray-set from a previous tomography study [*Rhodes & Davies*, 1997]. We define the arrival time residuals as the 'observed' arrival times from the MCMs minus the 'predicted' arrival times from the reference model. The arrival time residuals are evaluated by integrating the slowness perturbations along each ray path.

3. Results

In Figure 1 we show the histograms of the arrival time residuals for the 6 models described above. All histograms are biased with non-zero negative means, i.e. on average the travel time of the "observed" rays is less than the travel times of the reference model implying the "synthetic Earth" is fast. The difference has the same sign as the body-wave versus normal mode discrepancy discussed in the introduction. It is entirely plausible to assume that it results from the inhomogeneous ray distribution, which leads to a biased sampling of the model Earth. Subduction zones are regions of faster than average velocity with higher than average ray sampling. Thus we suggest that the preferential sampling of the faster than average regions produces the biased histograms.

To test our hypothesis we evaluate histograms for events in selected regions in the North Atlantic and the Andes for the reference MODEL 1. Figure 2 shows that the North Atlantic histogram is biased towards positive values, as expected given that the majority of events lies above the slow velocities produced in the MCM from hot upwelling mantle beneath the North Atlantic spreading ridge (see the companion paper [*Bunge & Davies*, 2000]). In contrast the Andes histogram is biased towards negative values, the same as found in the whole "Earth" histogram (Figure 1). Of course, this region is characterized by subduction of the Nazca plate, and the majority of events are located near the highest velocity region of the subducted slab. We proceed one step further in testing the hypothesis that co-location of earthquakes and fast seismic structures acts to bias our results by breaking this correlation and rotating MODEL 6 by 90 degrees east in longitude relative to the Earth. Clearly, in this case the sources are no longer preferentially located in the fast shallow structures, and we see from Figure 3 that the arrival-time bias has largely disappeared.

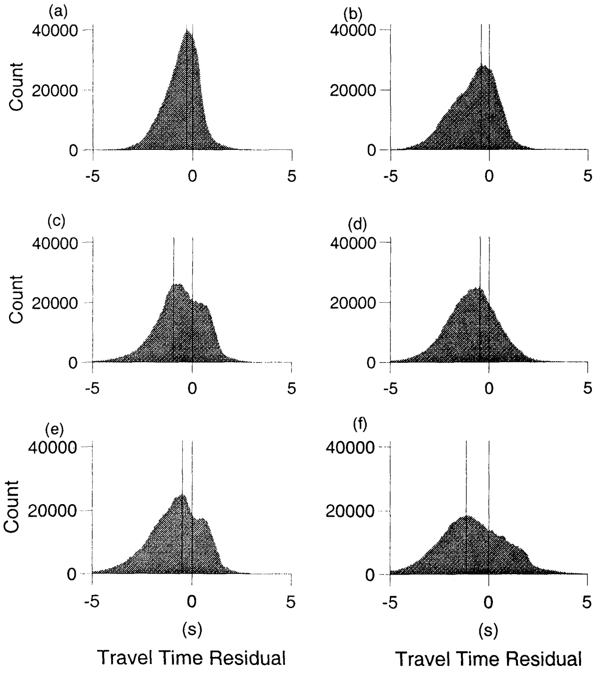

Figure 1. (a)-(f) Histograms of P-wave arrival time residuals for MCM (1)-(6) (see Table 1). Vertical line passes through mode of histogram.

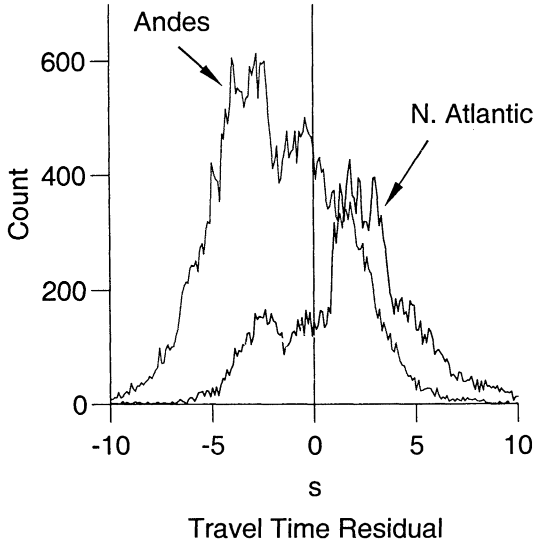

Figure 2. Histograms of P-wave arrival time residuals (Model 1) for events in a rectangular box surrounding the north Mid-Atlantic, and for all events in a box in South America including all of the Andes.

4. Discussion

Seismically fast travel time residuals appear to be a robust result for heterogeneity derived from MCM modeling. We therefore suggest that it is a signature one should expect from the real Earth. Thus biased sampling by typical body-wave raypaths of Earth structure may provide a further explanation for the discrepancy between body-wave traveltimes and predictions based on normal-mode models. We note that the discrepancy is smallest for the reference MODEL 1 (Figure 1a), which has the least resistance for subducting slabs to penetrate into the lower mantle, with a relatively small viscosity increase and no phase change at 670km. While upper mantle structure is similar for all the circulation models, the slabs do not accumulate as strongly in the upper part of the lower mantle in MODEL 1, which may be the reason why the mean of the histogram is not as negative in this case. If this interpretation is indeed correct, it implies that it is the extension of subducting slabs into the top of the lower mantle and not their well defined (by Wadati-Benioff zones) upper-mantle portions, that is most significant for generating this negative mean.

It is difficult to quantify the effect of the biased sampling on the discrepancy. It does vary slightly with mantle circulation model, and the current models are not quite at realistic Earth-like vigor but have thermal lithospheres of order 150-200km thick. It will also vary with the choice of dVp / dT as a function of depth, a poorly known parameter. For illustration, if Earth's seismic structure was the same as models (1-6) here then the negative mean of the histograms implies that the biased ray sampling could account for 0.5 - 0.9 s of the P-wave discrepancy. This would still leave a discrepancy to be explained by the other candidates discussed in the Introduction (e.g. attenuation, wave-front healing, continent bias etc.). It suggests that before a quantitative estimate of attenuation in the Earth is extracted from the apparent dispersion (the fact that higher frequency waves seem to travel faster than lower frequency waves), this effect (as well as the others just mentioned) will need to be well estimated and accounted for, so that the actual dispersion can be separated from the apparent dispersion.

Different distributions of rays would lead to different levels of bias. The ray set utilized here though will dominate most global body wave studies. The addition of core (e.g. PKP) and bounce (PP, PPP) phases might be expected to reduce the bias somewhat. Adding in crustal and lithosphere structure, as in Crust 5.1 *Mooney et al.* [1998] and 3SMAC *Nataf & Ricard* [1981] would also change the sampling bias.

5. Conclusion

We have shown that mantle heterogeneity structure derived from MCM modeling is characterized by histograms of travel time residuals with negative means. This implies that the sampled 3D Earth seems faster than its underlying 1D reference Earth. The 1D reference Earth can be considered to be derived from normal mode data that give a good global average with little geographic bias due to the natural averaging process involved in global free oscillations. The sampling of the 3D Earth mimics well the travel time datasets used in summarizing the traveltimes of body-waves.

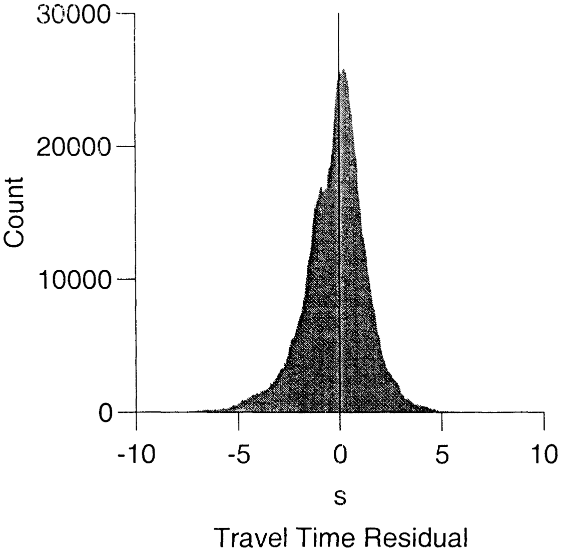

Figure 3. Histogram of arrival-time residuals for model 6 after the model has been rotated 90 degrees eastwards to break the strong correlation between ray-paths and subduction generated fast velocity anomalies.

We ascribe this result to the inhomogeneous sampling of the Earth arising from the non-random distribution of events. In particular the majority of events are in subduction zones, which are faster than average velocity structures. Even if our explanation for the difference was incorrect, the fact that a difference exists has implications for estimating the dispersion of seismic waves in Earth. We must estimate this bias arising from inhomogeneous sampling before we can attribute the remaining signal to dispersion. We note that we would also need to account for wave healing phenomena. This is where the first arriving rays sample the faster anomalies and therefore using their travel times could also give a biased "fast" estimate of the velocity structure (*Wielandt*[1987], *Nolet and Moser*[1993], *Gudmundsson*[1996]). Therefore estimates of Earth attenuation based on a straightforward reconciliation of body-wave and normal mode data must be treated with caution.

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References

Bunge, H.-P. and J.H. Davies Tomographic images of a mantle circulation model, *Geophys. Res. Lett.*, 2000.

Bunge, H.-P. and J.R. Baumgardner, Mantle convection modeling on parallel virtual machines, *Computers in Physics, 9,* 207-215, 1995.

Bunge, H.-P., M.A. Richards, C. Lithgow-Bertelloni, J.R. Baumgardner, S.P. Grand and B. Romanowicz, Time scales and heterogeneous structure in geodynamic earth models, *Science, 280,* 91-95, 1998.

Dahlen, F.A. and J. Tromp, *Theoretical Global Seismology,* 1025 pp., Princeton University Press, 1998.

Duffy, T.S. and T.J. Ahrens, Sound velocities at high pressure and temperature and their geophysical implications *J. Geophys. Res., 97,* 4503-4520, 1992.

Engdahl, E.R., van der Hilst, R and R. Buland, Global teleseismic earthquake relocation with improved travel times and procedures for depth determination *Bull. Seism. Soc. Am., 88,* 722-743, 1998.

Gilbert, F., and A.M. Dziewonski, An application of normal mode theory to the retrieval of structural parameters and source mechanisms from seismic spectra, *Phil. Trans. R. Soc. London, Ser. A., 278,* 187-269, 1975.

Gudmundsson O, On the effect of diffraction on traveltime measurements *Geophys. J. Int., 124,*, 304-314, 1996.

Hager, B.H, and M.A. Richards, Long-wavelength variations in Earth's geoid: Physical models and dynamical implications, *Phil. Trans. R. Soc. London, Ser. A., 328,* 309-327, 1989.

Hales, A.L., and J.L. Roberts, Shear velocities in the lower mantle and the radius of the core, *Bull. Seism. Soc. Am., 60,* 1427-1436, 1970.

Jeffreys, H., Damping of S-waves, *Nature, 208,* 675, 1965.

Karato, S.-I., Importance of anelasticity in the interpretation of seismic tomography, *Geophys. Res. Lett.*, 20, 1623-1626, 1993.

Kennett, B.L.N. and E.R. Engdahl, Traveltimes for global earthquake location and phase identification, *Geophys. J. Int.,105,* 429-465, 1991.

Lithgow-Bertelloni, C. and M.A. Richards, The dynamics of Cenozoic and Mesozoic plate motions, *Rev. Geophysics, 36, 27-78,* 1998.

Liu, H.-S., D.L. Anderson and H. Kanamori, Velocity dispersion due to anelasticity; implications for seismology and mantle composition, *J. R. Astr. Soc., 47,* 41-58, 1976.

Mitrovica, J.X., Haskell [1935] revisited, *J. Geophys. Res., 101,* 555-569, 1996.

Mooney, W. D., G. Laske, and T.G. Masters, CRUST 5.1: A global crustal model at 5 degree by 5 degree, *J. Geophys. Res., 103,* 727-747, 1998.

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,* 101-122, 1996.

Nolet, G., and T.-J. Moser, Teleseismic delay times in a 3-D Earth and a new look at the S discrepancy, *Geophys. J. Int.,114,* 185-195, 1993.

Rhodes, M., and J.H. Davies, Lower mantle P-wave tomography using an a priori 3D velocity model (abstract), *Eos Trans. AGU, 78,* Fall Meeting suppl., 459, 1997.

van der Hilst, R.D, Widiyantoro, S. and E.R. Engdahl, Evidence for deep mantle circulation from global tomography, *Nature, 386,* 578-584, 1997.

Wielandt, E., On the validity of the ray approximation for interpreting delay times, in *Seismic tomography*, ed. G. Nolet, D. Reidel Co., Dodrecht, 85, 1987.

J. Huw Davies, Department of Earth Sciences, University of Liverpool, Liverpool, L69 3PG, UK, (e-mail: davies@liverpool.ac.uk)

Hans-Peter Bunge, Department of Geosciences, Guyot Hall, Princeton University, Princeton, N.J. 08544, USA, (email: bunge@princeton.edu)

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