Geophys. J. Int. (2009) **177,** 99–103 doi: 10.1111/j.1365-246X.2009.04056.x

Reply to comment by S. Crampin on 'Global anisotropic phase velocity maps for higher mode Love and Rayleigh waves'

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Accepted 2008 November 24. Received 2008 November 13; in original form 2008 November 13

SUMMARY

We thank Stuart Crampin for his interest in our recent paper but respectfully disagree when he argues that our measurements are not appropriate for inferring mantle anisotropy. The approximations we made are common and perfectly acceptable for the considered frequency band. The comment ignores a large part of the literature which investigated this. We will discuss the validity of our approximations in the measuring process and the interpretation based on published arguments as well as additional tests based on numerical modelling using the spectral element method and a fully 3-D anisotropic Earth model.

Key words: Inverse theory; Surface waves and free oscillations; Seismic anisotropy; Seismic tomography.

1 INTRODUCTION

Anisotropy has a variety of effects on surface waves: (i) the Love-Rayleigh discrepancy (Anderson 1961), (ii) azimuthal dependence of wave speeds (Smith & Dahlen 1973) and (iii) polarization anomalies (Crampin 1975). Surface wave seismologists mainly rely on phase measurements to explain (i) and (ii). Attempts have been made to investigate (iii), but the analysis is delicate. In his comment, Crampin (2008) argues that in a general anisotropic medium, surface wave modes do not separate into Rayleigh wave modes on the vertical and radial component and Love wave modes on the transverse component which contaminates traditional phase measurements. While this is of course correct in principle, the strength of the Love-Rayleigh coupling depends very much on the frequency band and the exact nature of the elastic medium (heterogeneity and/or anisotropy). We were a bit surprised that hundreds of other papers relying on the same approximations were not mentioned in the comment. A good review of the effect of anisotropy on seismic wave propagation and observation may be found in Maupin & Park (2007). The two examples provided in the comment are particularly unhelpful because they are in frequency bands (6–12 s and the Mhz band) far removed from our carefully chosen frequency band (35–150 s). Aside for documented cases of Love-Rayleigh coupling in our frequency band, we performed for this reply exact calculations in the 3-D model of Montagner (2002) to illustrate deviations from JWKB theory that should be expected. Crampin (2008) also questions the legitimacy of treating anisotropy by perturbation analysis. From seismology (Maupin & Park 2007; Montagner 2007) and mineral physics (Mainprice *et al.* 2000), the expected lateral variations of anisotropy are of the order of a few percent which can easily be treated by perturbation, provided that the appropriate theory for the quantities of interest has been expressed in terms of anisotropic parameters and that the right measurements are made. Finally we will discuss published tests that show that our separate Love and Rayleigh wave observations are indeed compatible with a unique underlying Earth model.

2 MEASUREMENTS

Our measurements rely on the validity of the JWKB approximation which is extensively discussed in Dahlen & Tromp (1998). To say that we use AMI (Lebedev *et al.* 2005) to make measurements is a stark oversimplification. We use AMI to get a starting model for our multimode waveform inversion and to select seismograms which are properly modelled by JWKB theory. Indeed, years of development resulted in powerful selection criteria which exclude all chance fits of non-JWKB features such as noise, scattering and mode conversions (see Lebedev *et al.* 2005, for detailed examples). The measurements are made using a full model space search for acceptable models which fit the waveforms, an extension of the work of Yoshizawa & Kennett (2002) to improve the uncertainty analysis (Visser *et al.* 2007). We have stayed clear of the frequency range in which coupling of Love and Rayleigh modes due to lateral heterogeneity is likely (Kennett 1995) and that same choice should minimize the anisotropic interactions. As soon as one gets out of this band, one needs to address deviations from the great circle and mode coupling, and the effects of anisotropy can be included via such coupling (Kennett 1998). Clear observations of Love-Rayleigh coupling in our frequency range are rare and extensively discussed in Maupin & Park (2007).

To illustrate the severity of mode coupling due to azimuthal anisotropy, we calculated synthetic seismograms using the spectral element method (Komatitsch & Tromp 2002a,b) in which the model of Montagner (2002) has been implemented. This upper mantle model is parameterized in variations of the azimuthally averaged SV-wave speed, radial S-wave anisotropy and azimuthal SV-wave anisotropy. Using the Aleutian Island earthquake of 13 March 2003 at 16h36, we generated seismograms for some 800 stations worldwide switching the azimuthal SV-wave anisotropy on and off and leaving the other parameters unchanged. For periods longer than 35 s, we saw clear Love-Rayleigh coupling on the transverse component expressed as a quasi-Rayleigh wave arriving in the coda of the fundamental mode Love wave for paths going to stations in California (azimuth 84° and a distance of 50°) (Fig. 1). This seismogram would not have passed the selection procedure in AMI because this complicated Love wave packet cannot be synthesized by a path-averaged model (Lebedev *et al.* 2005). For most other stations there was no noticeable effect on the transverse component. On the vertical component, we saw a clear shift of the Rayleigh fundamental and first higher modes by about 5 s. Such a time shift was noticeable on most stations and perfectly predicted by the formulae of Smith & Dahlen (1973) and thus easily measured by our method (Fig. 2). On high frequency seismograms (periods shorter than 35 s), we saw clear waveform distortions due to coupling of fundamental and higher mode Love and Rayleigh waves (Figs 3 and 4). This simple experiment shows that in our selected frequency range, most seismograms will not exhibit mode coupling due to azimuthal anisotropy and those which do would be eliminated by AMI. We agree with Crampin that in a higher frequency range the problem can be severe and should be investigated by more detailed 3-D modelling.

Crampin also questions the effectiveness of the mode-separation technique. Many authors used a variety of independent techniques (see references in Visser *et al.* 2008). We found that overlapping measurements by completely independent techniques are remarkably consistent (Visser *et al.* 2007). If mode coupling would bias the measurements, different techniques would be affected in different ways and the agreement would be poor. Furthermore, it is unlikely that the inversion of contaminated measurements could achieve such high variance reductions and show such a consistency between different independent studies.

3 AZIMUTHALLY VARYING PHASE VELOCITY MAPS

Crampin further questions that anisotropy can be modelled by perturbation from a (transversely) isotropic reference state. His argument is that for shear wave splitting the isotropic reference state has a degenerate Christoffel matrix and perturbation theory is therefore not appropriate. It should then also not be applicable to surface waves. The degeneracy can easily be broken by an infinitesimal change in the elastic moduli thus working from a state that is macroscopically indistinguishable from (transverse) isotropy. Perturbation theory will then directly be valid. Jech & Psencik (1989) showed that degenerate perturbation theory is adequate for perturbations up to 10 percent in phase speed and polarization polarization vectors, but that the expressions depend non-linearly on perturbations of the elastic parameters. The problem for splitting measurements is that the usual parameters (time shift and fast polarization) do not depend on the elastic parameters in a simple way. This inconvenience is most elegantly solved by defining the splitting intensity (Chevrot 2000) or a generalisation thereof (Sieminski *et al.* 2007, 2008) a measurable quantity which is linearly related to elastic parameters and can easily be treated by perturbation analysis. For surface waves, phase velocity perturbations depend linearly on perturbations of elastic parameters and in the case of weak anisotropy simple expression can be derived for azimuthal variations (Smith & Dahlen 1973). The only question is if anisotropy is weak in the mantle. From various data sets in seismology, mantle anisotropy appears to be of the order of a few percent (Maupin & Park 2007; Montagner 2007). This is also what you would expect from mineral

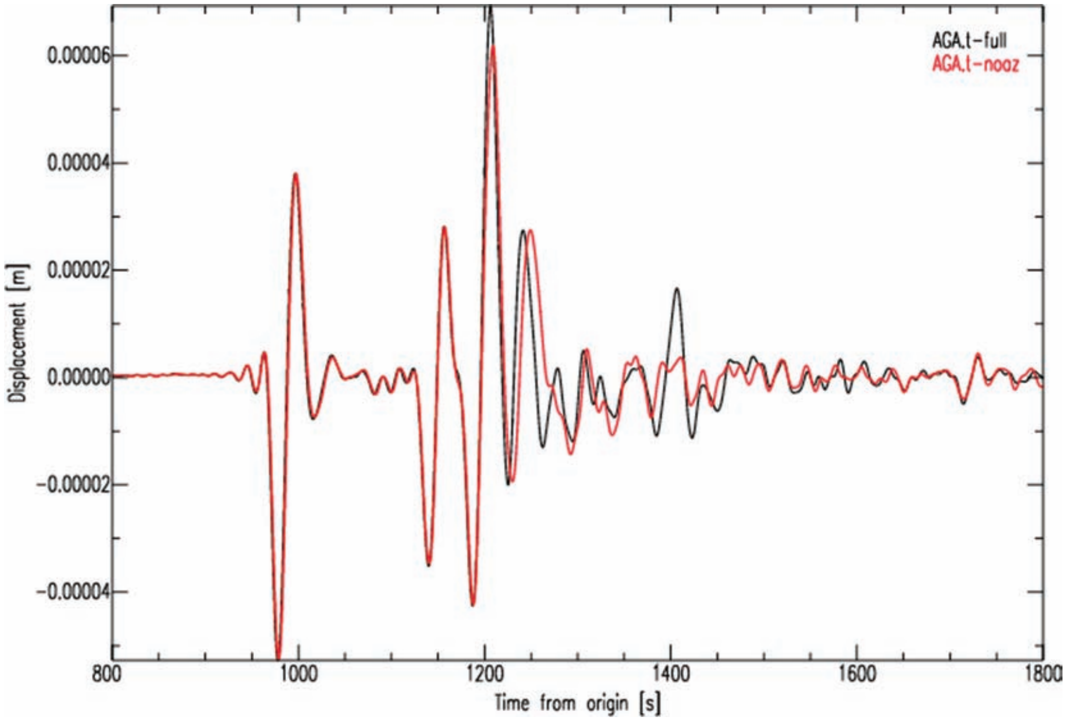

Figure 1. Transverse component seismograms recorded at station AGA using full anisotropy (black) and transverse isotropy only (red). The seismograms are low-pass filtered at 35 s. The SH wave arrives around 950 s and the Love wave around 1120 s. Note the quasi-Rayleigh wave starting at 1250 s.

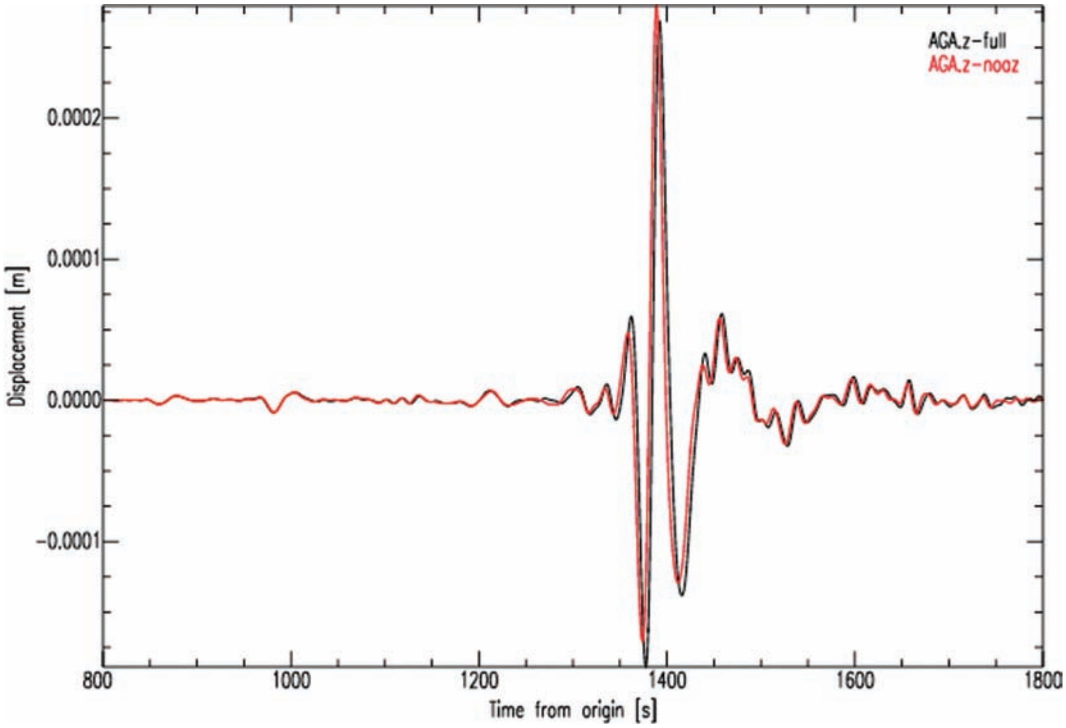

Figure 2. Vertical component seismograms recorded at station AGA using full anisotropy (black) and transverse isotropy only (red). The seismograms are low-pass filtered at 35 s. The small *SV* wave arrives around 950 s and the Rayleigh wave after 1350 s. Note the uniform 5 s shift of the fundamental and first higher-mode (around 1300 s) Rayleigh waves.

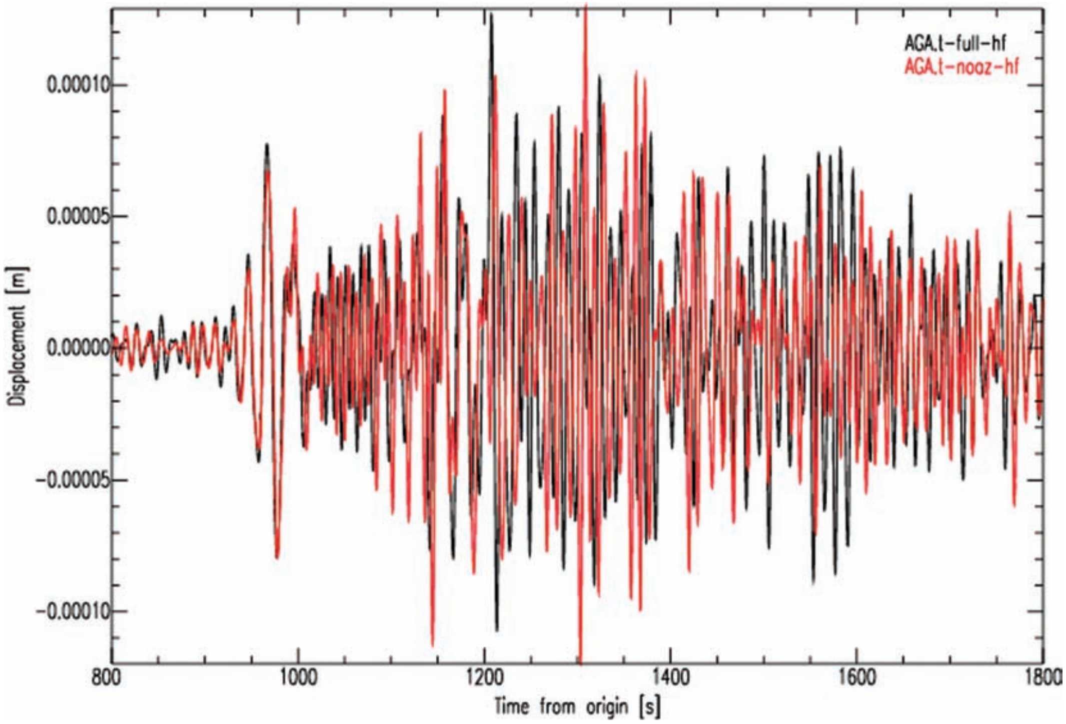

Figure 3. Transverse component seismograms recorded at station AGA using full anisotropy (black) and transverse isotropy only (red). The seismograms are high-pass filtered at 35 s. Note the clear waveform distortions of the fundamental-mode Love wave and the first overtones arriving just before.

physics measurements assuming partial alignment of anisotropic polycrystals (Mainprice *et al.* 2000). We therefore don't see any indication that perturbation theory should be questioned at this stage.

4 INTERPRETATION

Crampin's last point concerns the interpretation of azimuthally varying phase velocity maps. He argues that biased measurements would

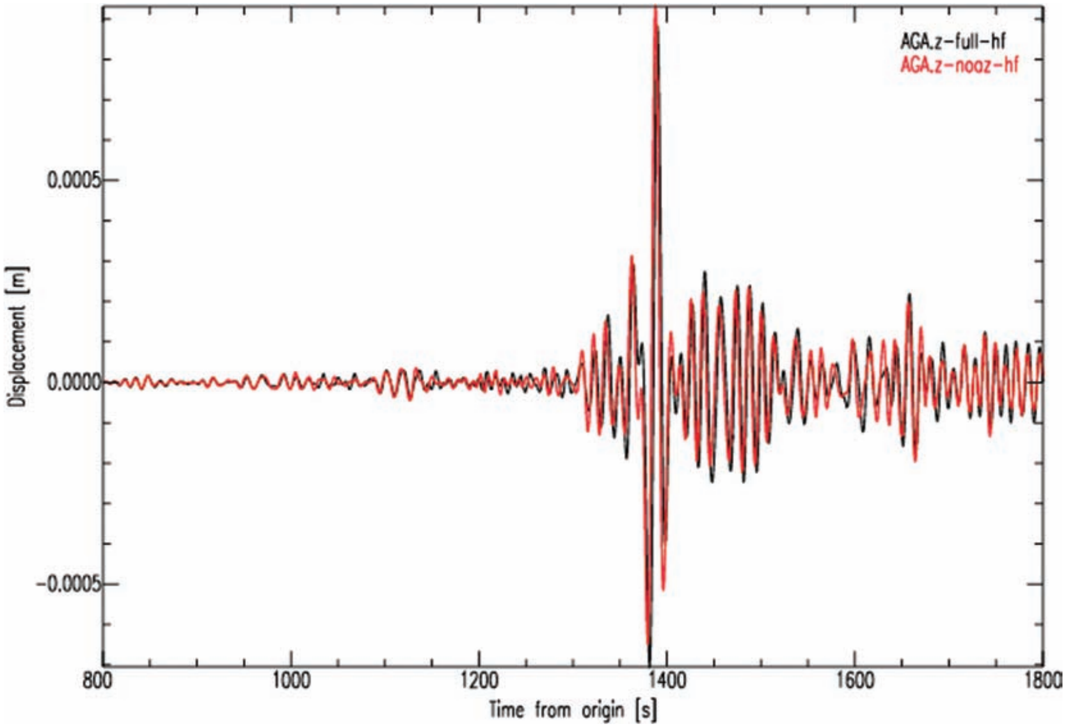

Figure 4. Vertical component seismograms recorded at station AGA using full anisotropy (black) and transverse isotropy only (red). The seismograms are high-pass filtered at 35 s. Note the clear waveform distortions of the fundamental-mode Rayleigh wave and the first overtones arriving just before.

produce maps which could not be inverted for a unique underlying Earth model. To our knowledge, nobody has ever undertaken a joint inversion of azimuthal variations of Love and Rayleigh waves. Instead, most people use the azimuthal maps to obtain azimuthally averaged phase velocities which are inverted for transversely isotropic models (e.g. Ekström & Dziewonski 1998). Trampert & van Heijst (2002) modelled azimuthal anisotropy in the transition zone using azimuthally varying phase velocity maps of Love wave overtones. They were precisely worried about the issues raised in Crampin's comment. Using a Backus-Gilbert approach, they created a linear combination of 2ψ Love wave overtone maps with the same depth sensitivity as a 2ψ Rayleigh fundamental mode map at 100 s. The agreement was remarkably good proving beyond doubt that the measurements are representative of a unique underlying Earth model. Trampert & van Heijst (2002) used the independent measurements of Van Heijst & Woodhouse (1999) which are in perfect agreement with ours (Visser *et al.* 2007). We are thus confident that our measurements are robust, and can be used to create azimuthally varying phase velocity maps which are representative of the Earth's mantle.

5 CONCLUSION

We agree with Crampin (2008) that polarization anomalies are a diagnostic tool for anisotropy, but we disagree that phase velocities cannot inform on mantle anisotropy. Phase velocity measurements, including overtones, are relatively easy to make and robust, and given some precautions are perfectly adequate to infer mantle anisotropy. Some ten years ago, the phase velocity coverage was poorer and polarization measurements were praised to break the trade-off between isotropic and anisotropic structures (Laske & Masters 1998). Since then, the measurement process has been automated, rejecting all seismograms with suspected scattering and mode coupling. The resulting coverage considerably reduces the trade-off (Trampert & Woodhouse 2003; Visser *et al.* 2008). Although there are sporadic attempts, polarization measurements of surface waves remain difficult to make and interpret (Maupin & Park 2007). Mode coupling observations at periods longer than 300 s have recently been used to infer azimuthal anisotropy (Beghein *et al.* 2008) and are a promising new source of information for mantle anisotropy.

ACKNOWLEDGMENTS

We thank Hanneke Paulssen for comments, Sergei Lebedev for discussions and Ebru Bozdag for performing the 3-D calculations. All computations were performed on the 128-node cluster financed by the Dutch National Science Foundation under grant number NWO:VICI1865.03.007.

REFERENCES

Anderson, D.L., 1961. Elastic wave propagation in layered anisotropic media, *J. geophys. Res.,* **66,** 2953–2963.

Beghein, C., Resovsky, J. & van der Hilst, R.D., 2008. The signal of mantle anisotropy on normal mode coupling, *Geophys. J. Int.,* **175,** 1209–1234.

Chevrot, S., 2000. Multichannel analysis of shear wave splitting, *J. geophys. Res.,* **105,** 21579–21590.

Crampin, S., 1975. Distinctive particle motion of surface waves as a diagnostic of anisotropic layering, *Geophys. J. R. astr. Soc.,* **83,** 75–92.

Crampin, S., 2009. Comment on 'Global anisotropic phase velocity maps for higher mode Love and Rayleigh waves' by Visser, Trampert and Kennett, *Geophys. J. Int.,* doi:10.1111/j.1365-246X.2008.04055.x.

Dahlen, F.A. & Tromp, J., 1998. *Theoretical global seismology,* Princeton University Press, Princeton.

Ekström, G. & Dziewonski, A.M., 1998. The unique anisotropy of the Pacific upper mantle, *Nature,* **394,** 168–172.

Jech, J. & Psencik, I., 1989. First-order perturbation method for anisotropic media, *Geophys. J. Int.,* **99,** 369–376.

Kennett, B.L.N., 1995. Approximations for surface-wave propagation in laterally varying media, *Geophys. J. Int.,* **122,** 470–478.

Kennett, B.L.N., 1998. Guided waves in three-dimensional structure, *Geophys. J. Int.,* **133,** 159–174.

Komatitsch, D. & Tromp, J., 2002a. Spectral-element simulations of global seismic wave propagation - I. Validation, *Geophys. J. Int.,* **149,** 390–412.

Komatitsch, D. & Tromp, J., 2002b. Spectral-element simulations of global seismic wave propagation - II. Three-dimensional models, oceans, rotation and self-gravitation, *Geophys. J. Int.,* **150,** 303–318.

Laske, G. & Masters, G., 1998. Surface-wave polarization data and global anisotropic structure, *Geophys. J. Int.,* **132,** 508–520.

Lebedev, S., Nolet, G., Meier, T. & van der Hilst, R.D., 2005. Automated multimode inversion of surface and S waveforms, *Geophys. J. Int.,* **162,** 951–964.

Mainprice, D., Barruol, G. & Ben Ismaïl, W., 2000. The seismic anisotropy of the Earth's mantle: from single crystal to polycrystal, in *Earth's Deep Interior: Mineral Physics and Tomography From the Atomic to the Global Scale,* Vol. 117, pp. 237–264, eds Karato, S., Forte, A., Liebermann, R., Masters, G. & Stixrude, L., Geophysical Monograph, *AGU,* Washington.

Maupin, V. & Park, J., 2007. Theory and Observations - Wave propagtion in anisotropic media, in *Treatise in Geophysics,* Vol. 1, pp. 289–321, eds Romanowicz, B. & Dziewonski, A.M., Elsevier, Amsterdam.

Montagner, J.P., 2002. Upper mantle low anisotropy channels below the pacific plate, *Earth planet. Sci. Lett.,* **202,** 263–274.

Montagner, J.P., 2007. Deep Earth structure—Upper mantle structure: global isotropic and anisotropic structure, in *Treatise in Geophysics,* Vol. 1, pp. 559–589, eds Romanowicz, B. & Dziewonski, A., Elsevier, Amsterdam.

Sieminski, A., Liu, Q., Trampert, J. & Tromp, J., 2007. Finite-frequency sensitivity of body waves to anisotropy based upon adjoint methods, *Geophys. J. Int.,* **171,** 368–389.

Sieminski, A., Paulssen, H., Trampert, J. & Tromp, J., 2008. Finite-frequency SKS splitting: measurement and sensitivity kernels, *Bull. seism. Soc. Am.,* **98,** 1797–1810.

Smith, M.L. & Dahlen, F.A., 1973. The azimuthal dependence of Love and Rayleigh wave propagation in a slightly anisotropic medium, *J. geophys. Res.,* **78,** 3321–3333.

Trampert, J. & van Heijst, H.J., 2002. Global azimuthal anisotropy in the transition zone, *Science,* **296,** 1297–1299.

Trampert, J. & Woodhouse, J.H., 2003. Global anisotropic phase velocity maps for fundamental mode surface waves between 40 and 150 s, *Geophys. J. Int.,* **154,** 154–165.

Van Heijst, H.J. & Woodhouse, J.H., 1999. Global high-resolution phase velocity distributions of overtone and fundamental-mode surface waves determined by mode branch stripping, *Geophys. J. Int.,* **137,** 601–620.

Visser, K., Lebedev, S., Trampert, J. & Kennett, B.L.N., 2007. Global love wave overtone measurements, *Geophys. Res. Lett.,* **34,** L03302, doi:10.1029/2006GL028671.

Visser, K., Trampert, J. & Kennett, B.L.N., 2008. Global anisotropic phase velocity maps for higher mode Love and Rayleigh waves, *Geophys. J. Int.,* **172,** 1016–1032.

Yoshizawa, K. & Kennett, B.L.N., 2002. Non-linear waveform inversion for surface waves with a neighbourhood algorithm—Application to multimode dispersion measurements, *Geophys. J. Int.,* **149,** 118–134.