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Traveltime dispersion in an isotropic elastic mantle: strong lower-mantle signal in differential-frequency residuals

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Recently, we developed a joint forward modelling approach to test geodynamic hypotheses directly against seismic observations. By computing 3-D global wave propagation in seismic models derived from simulations of mantle flow, synthetic seismograms are generated independent of any seismic data. Here, we now show that this is also an excellent tool to study wavefield effects in a consistent manner, as length scales and magnitudes of seismic heterogeneity in the models are constrained by the dynamics of the flow. In this study, we quantify the traveltime dispersion of P- and S-waves caused by diffraction in our elastic and isotropic 3-D synthetic seismic structures. Intrinsic attenuation (i.e. dissipation of seismic energy) is deliberately neglected, so that any variation of traveltimes with frequency can be attributed to structural effects. Traveltime residuals are measured at 15, 22.5, 34 and 51 s dominant periods by cross-correlation of 3-D and 1-D synthetic waveforms. Additional simulations are performed for a model in which 3-D structure is removed in the upper 800 km to isolate the dispersion signal of the lower mantle.

We find that the structural length scales inherent to a vigorously convecting mantle give rise to significant diffraction-induced body-wave traveltime dispersion. For both P- and S-waves, the difference between long-period and short-period residuals for a given source–receiver pair can reach up to several seconds for the period bands considered here. In general, these 'differential-frequency' residuals tend to increase in magnitude with increasing short-period delay. Furthermore, the long-period signal typically is smaller in magnitude than the short-period one; that is, wave-front healing is efficient independent of the sign of the residuals. Unlike the single-frequency residuals, the differential-frequency residuals are surprisingly similar between the 'lower-mantle' and the 'whole-mantle' model for corresponding source–receiver pairs. The similarity is more pronounced in case of S-waves and varies between different combinations of period bands. The traveltime delay acquired in the upper mantle seems to cancel in these differential signals depending on the associated wavelengths and the length scales of structure at shallow depth. The standard deviations of dispersion between the longest (51 s) and the shortest (15 s) period considered here are 0.6 and 1.0 s for P- and S-waves, respectively. In the lower-mantle model, standard deviations are 0.3 and 0.6 s, respectively, which gives an average lower-mantle contribution to the total dispersion of 50 per cent for P- and 60 per cent for S-waves. Differential-frequency residuals may prove useful to precondition tomographic inversions and we will discuss their potential benefits for constraining lower-mantle structure.