The influence of horizontally elongated fine scale heterogeneity on surface wave phase speeds and apparent radial anisotropy

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Seismic anisotropy has been the subject of extensive research for decades in structural seismology. It can arise from different mechanisms, including intrinsic anisotropy from Earth materials, and apparent anisotropy from structural characteristics such as fine layering and/or alignment due to formation and deformation in the Earth. It is essentially hard to distinguish the intrinsic and apparent seismic anisotropy. Recent studies on high-frequency (>1 Hz) wave scattering have suggested the existence of fine-scale horizontally elongated random heterogeneity in the lithosphere(Furumura and Kennett, 2005;Kennett and Furumura, 2008;Kennett et al., 2016), which may cause some changes in surface wave phase speeds and may generate apparent radial anisotropy in surface wave tomography models.

To investigate the effects of such heterogeneity on the propagation of surface waves, not only high-frequency signals but also in longer-period(> 20 sec.), we performed two kinds of numerical experiments: 1-D normal-mode calculations and 2-D FDM simulation of seismic wave propagation. In the normal-mode approach, we first generate a number of isotropic 1-D models, which includes random fluctuations in a specific depth range, then calculate dispersion curves for each model using MINOS(Masters et al., 2011) and compute the average phase velocity perturbation from a reference model. This 1-D approach can also be done analytically based on the effective medium theory(Backus, 1962), which enables us to estimate an effective anisotropic model that can also be used to compute normal modes.

We also performed a series of 2-D finite difference method simulation using models with background velocity from the iasp91 model(Kennett &Engdahl, 1991), incorporating horizontally elongated fine-scale heterogeneity with a variety of combinations of different parameters of heterogeneity distributions,such as (1)aspect ratio of heterogeneity, (2)strength of heterogeneity, and (3)depth range of heterogeneous layer. Then, the average phase velocities of fundamental-mode Love and Rayleigh waves are estimated using the inter-station waveform fitting method(Hamada & Yoshizawa, 2015). By comparing the average phase velocity among the 2-D random models with different heterogeneity parameters, we can quantify the influence of each parameter on apparent radial anisotropy.

Through these numerical experiments, we have found that horizontally elongated fine-scale heterogeneity(with relatively large horizontal correlation length over 10 km, with the strength of heterogeneity of greater than 2%) can create non-negligible effects on the phase speeds of Rayleigh waves, but not for Love waves, creating apparent radial anisotropy(SH wave travels faster than SV). Such heterogeneity models also generate high-frequency scattering, and has the effect of guiding seismic waves through multiple forward scattering(e.g., Kennett et al., 2016). Results from 1-D and 2-D simulations with similar model parameter setting provide similar phase speed perturbations. Among the three parameters mentioned above, the strength and the aspect ratio directly affect the level of phase speed drop, i.e., enlarging them will make Rayleigh waves travel significantly slower, while the depth range controls both the level and period range of phase speed drop. A specific model with 5% RMS heterogeneity, the aspect ratio of 20:1, the depth range from 35 to 120km will create about 2% velocity drop of fundamental-mode Rayleigh wave(while Love wave is barely affected). This result fits well with the theoretical prediction on this issue(e.g., Fichtner et al., 2013), and thus provide another plausible cause for the observed anisotropy in the lithosphere and asthenosphere.

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