

3D imaging of the Earth's lithosphere using noise from ocean waves

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SUMMARY

The lithosphere is the rigid outer shell of the Earth, composed of the crust and the rigid uppermost mantle. The lateral variation of lithosphere is believed to be closely related to the foci of intraplate earthquakes and volcanism, the location of large ore deposits and diamond-bearing kimberlites, and the formation of oil/gas-bearing sedimentary basins. Understanding the fine-scale structure of the lithosphere is therefore one of the most fundamental tasks in Earth sciences, and has important implications for society in terms of economic prosperity and hazard mitigation.

Seismic tomography is the main technique available to image the subsurface structure of the Earth across a range of scales. Conventional seismic tomography exploits the seismic waves emitted by earthquakes. However, because most large earthquakes occur at plate boundaries and most continents, including Australia, are not seismically active, earthquake-based tomography suffers from uneven distributions of earthquakes and has difficulties in deciphering fine-scale structures of the Earth in seismically quiet continents.

In the past decade, the advent of ambient noise tomography (ANT) has revolutionized seismic tomography because it can overcome the limitations of conventional earthquake surface wave tomography. This technique uses diffuse background seismic energy, mostly comes from the interaction of ocean waves with the crust. Empirical Green's functions of surface waves passing between a pair of stations are extracted by cross-correlating continuous time series of ambient noise. Within a regional seismic array, all inter-station measurements of surface-wave dispersion can be measured and tomography can be performed to image the underlying lithospheric structure. In this study, we demonstrate the applications of broadband ANT in mapping fine-scale lithosphere structures around the world using continuous seismic data.

Key words: Lithosphere, surface wave, ambient noise, tomography

INTRODUCTION

The lithosphere is the rigid outer shell of the Earth, composed of the crust and the rigid uppermost mantle. Underlying the lithosphere is a weaker, viscous layer of upper mantle, called the asthenosphere, which is thought to lubricate the movement of overriding lithospheric plates. Although the base of the lithosphere is commonly thought of as a first-order boundary or structural discontinuity, there are no strong *a priori* physical arguments why it should be a global sharp boundary. Factors that can contribute to ~~produce~~ a relatively sharp boundary at the base of the lithosphere include the presence of melt lenses, sharp change in fluid content (mainly H₂O), and strong shearing due to the horizontal motion of the plate, among others. Some or all of these factors are likely to be more common in oceanic environments [e.g. Afonso et al., 2008b; Karato, 2012; Kawakatsu et al., 2009; Rychert and Shearer, 2011; Olugboji et al., 2013; Naif et al., 2013], where evidence for sharp seismic discontinuities (which in *some* cases *may* coincide with the base of the lithosphere) is clear [e.g. Kawakatsu et al., 2009; Olugboji et al., 2013]. However, geochemical, geophysical and numerical evidence suggest that, at least beneath some continents, this boundary is more like a gradual "transitional zone" and subject to complex physicochemical interactions between the overlying lithospheric plate and the sublithospheric upper mantle. Some of these interactions include the episodic transfer of mass and energy from the asthenosphere to the base of the lithosphere (e.g. percolation of low-degree melts, refertilization, underplating) and from the lithosphere to the asthenosphere (e.g. lithospheric downwellings or drips, small-scale convection). This dynamic interaction results in strong lateral and vertical variations of the lithosphere in terms of thickness, temperature and chemical composition. The lateral variation is believed to be closely related to the foci of intraplate earthquakes and volcanism, the location of large ore deposits and diamond-bearing kimberlites, and the formation of oil/gas-bearing sedimentary basins. Understanding the fine-scale structure of the lithosphere is therefore one of the most fundamental tasks in Earth sciences, and has important implications for society in terms of economic prosperity and hazard mitigation.

Seismic tomography is the main technique available to image the subsurface structure of the Earth across a range of scales. This technique is similar in principle to CT scans that are used in medicine. Based on a CT scan, doctors can “see” organs and bones inside human bodies. Likewise, through seismic tomography, we can “see” different structures beneath volcanoes, mountains, sedimentary basins and other geological features. Conventional seismic tomography exploits the seismic waves emitted by earthquakes. However, because most large earthquakes occur at plate boundaries, and most continents, including Australia, are not seismically active, earthquake-based tomography suffers from uneven distributions of earthquakes and has difficulties in deciphering fine-scale structures of the Earth in seismically quiet continents.

Since Shapiro et al. (2005) first showed that group velocity dispersion maps can be obtained from ambient noise, ANT has become popular for imaging crustal and uppermost mantle structure. Compared to earthquake-based surface wave tomography, ANT frees surface wave tomography from its dependence on earthquakes. ANT, in effect, becomes a controlled-source technique; that is, the path coverage in ANT is controlled by desired configurations of seismic stations. To date, most ANT studies focus on surface waves at periods shorter than 40/50 s because ambient noise in this period range is strong and surface waves with high signal-to-noise ratio (SNR) can be obtained. However, more and more studies have demonstrated that long-period surface waves (>50 s) can also be extracted from ambient noise. For example, Shapiro and Campillo (2004) first extracted surface wave group velocity dispersion curves up to 125 s between two stations with an interstation distance longer than 2000 km; Nishida et al. (2009) used more than 10 years of ambient noise data to extract surface waves at periods of 100 to 400 s between teleseismic station pairs; Yang (2014) obtained teleseismic long-period surface waves from cross correlations of two-year ambient noise data and used them in regional surface wave tomography.

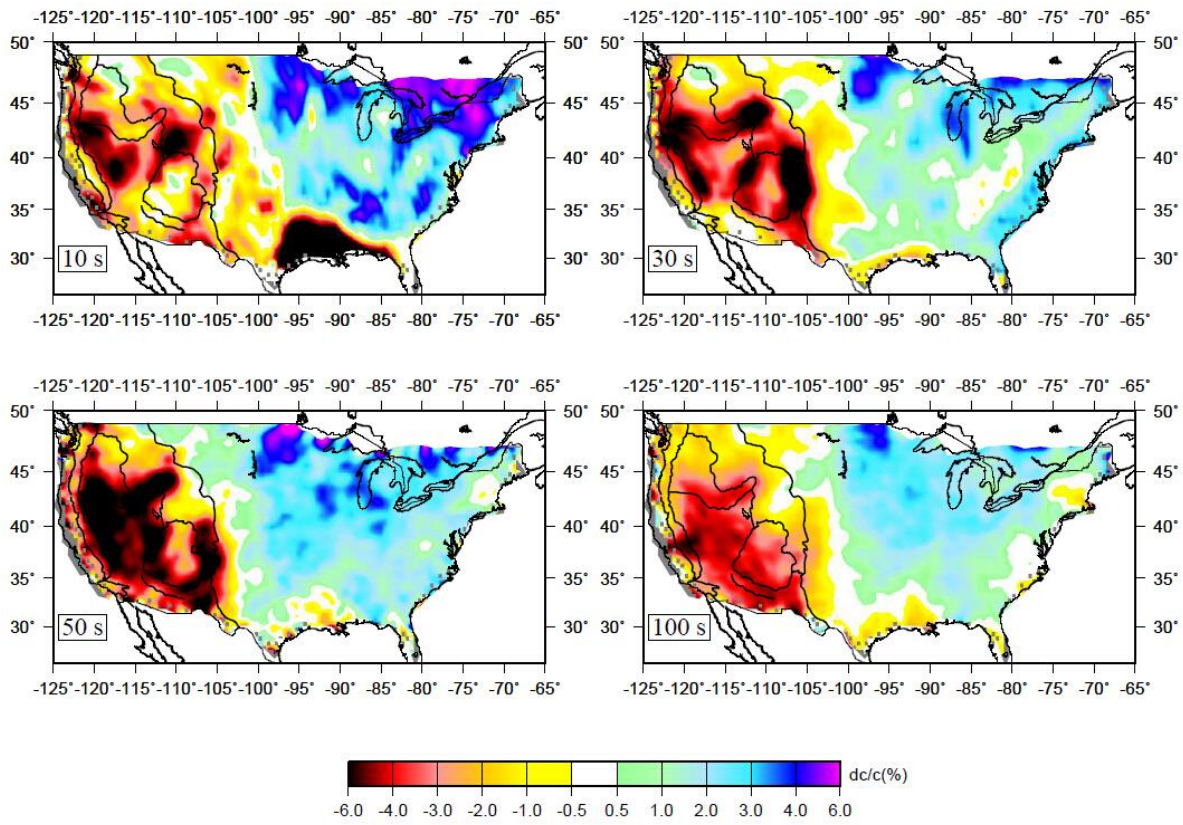
Broadband surface waves from ambient noise can be inverted for structures at depths from the surface down to the lithosphere and asthenosphere. In this study, we demonstrate the feasibility using broadband surface wave to image structures of whole lithosphere from the surface down to ~250 km depth.

METHOD AND RESULTS

We choose the western USA as a case study to illustrate the feasibility of our method. The western USA has complicated tectonic features shaped by complex tectonics in the past, and it was covered by the USArray Transportable Array (TA) with a station spacing of ~70 km. Numerous surface wave tomography studies have been carried out in this region, so the western USA provides a perfect place to test our finite-frequency ANT method.

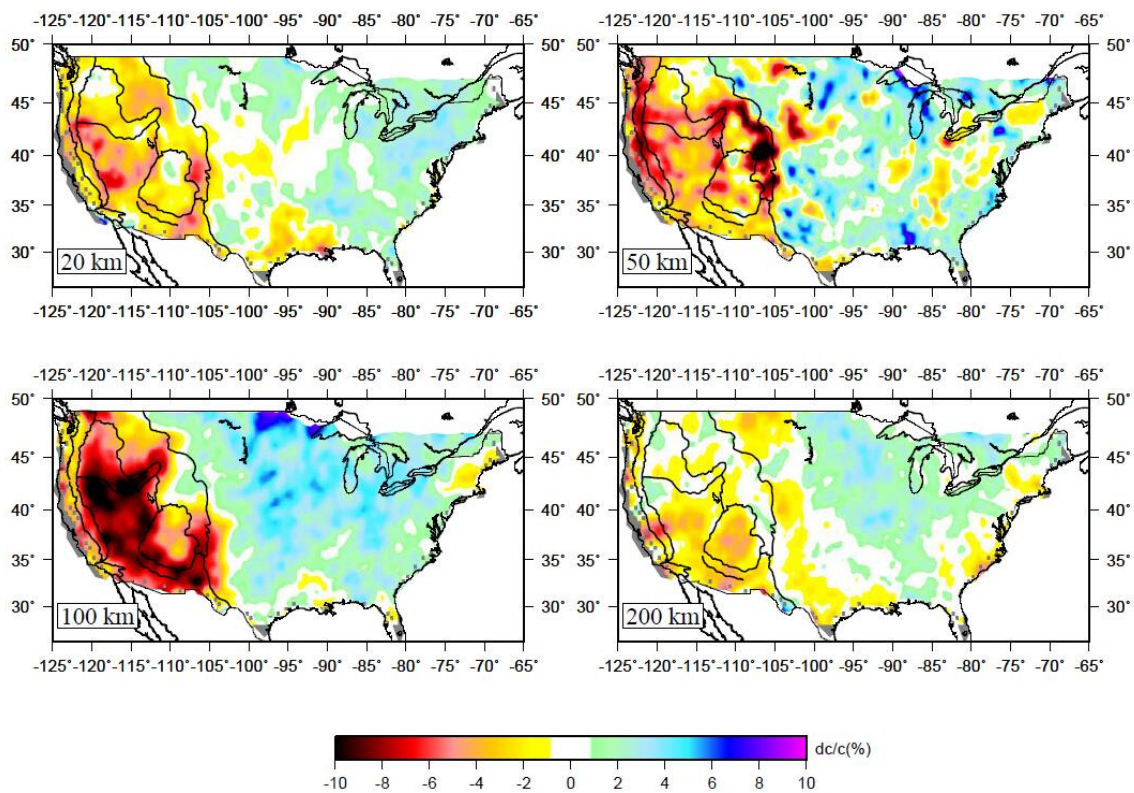
We extract broadband cross-correlation functions (CCFs) by cross-correlating continuous vertical-component ambient noise data recorded by ~900 TA stations operating during 2006-2012 in the western USA. We use data processing procedures similar to those described by Bensen et al. (2007). We then calculate the 2-D phase sensitivity kernel based on the Born approximation for interstation surface wave between each station pair and use a standard and linearized inversion technique (Tarantola and Valette, 1982) to perform tomography to obtain phase velocity maps at individual periods. Examples of phase velocity maps at selected periods are plotted in Fig. 1

Phase velocity maps provide us with the integrated velocity structure of the crust because the surface waves at individual periods are sensitive to a broad depth range. In order to investigate the structures at specific depths, we invert local phase velocity dispersion curves for depth-dependent shear velocities. We extract local dispersion curves at 10-150 s periods from the inverted phase velocity maps. We invert the extracted local dispersion curves for 1D Vs profiles using a Bayesian Monte-Carlo method developed by *Afonso et al* [2013a,b]. The horizontal slices of our final 3D model at various depths are shown in Figure 2, and some transects presented in Figure 3.



Phase velocity perturbation

Figure 1 Phase velocity maps at 10, 30, 50 and 100 s period, plotted as the perturbation relative to the average at each period.



Shear velocity perturbation

Figure 2 Shear velocity maps of the resulting 3D model at 20, 50, 100 and 200 km depths, plotted as the perturbation relative to the average at each depth.

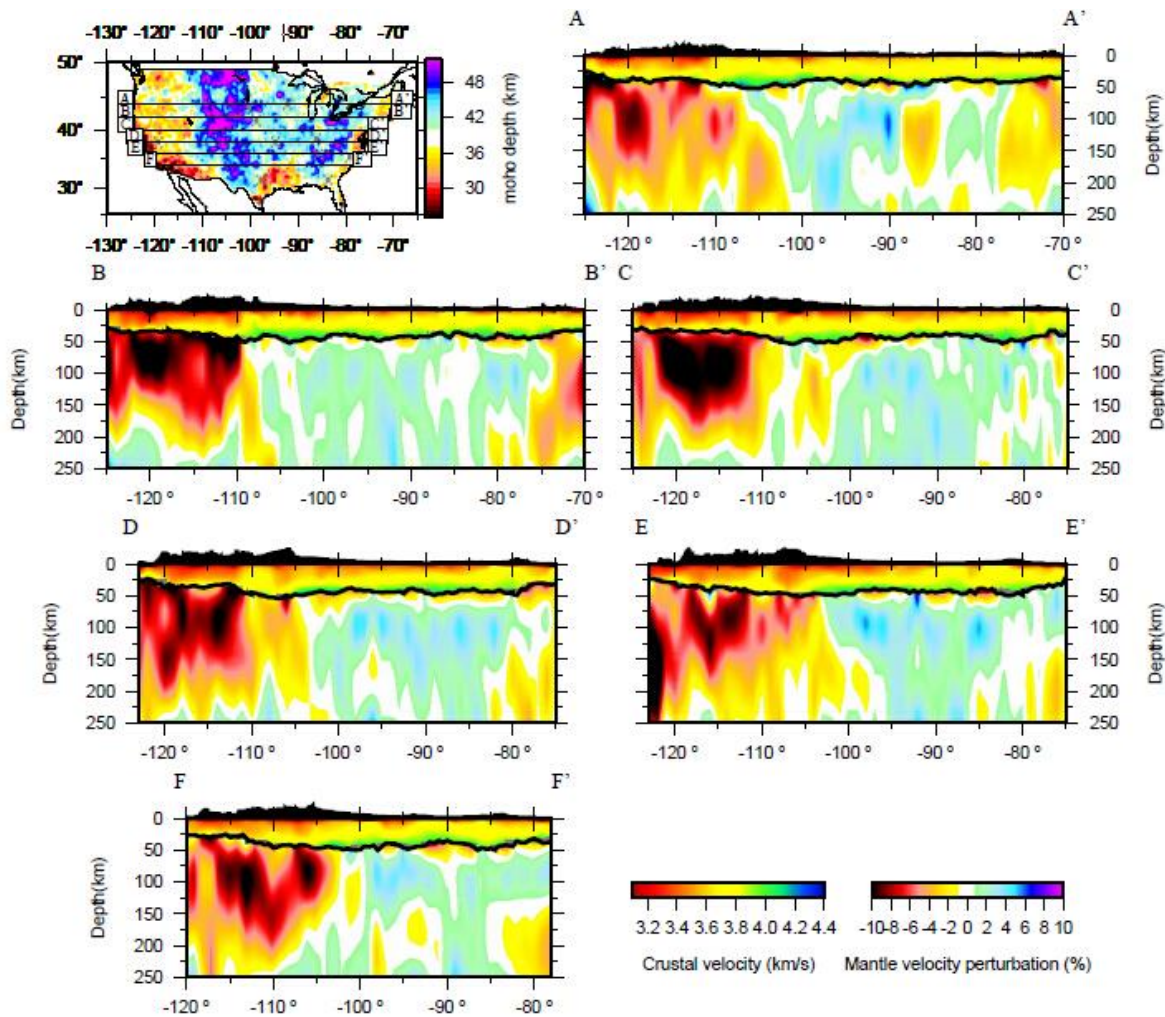


Figure 3 Transects of the resulting 3D shear velocity models from west to east of USA.

CONCLUSIONS

We demonstrate the feasibility of broadband Ambient noise tomography (ANT) in mapping lithosphere structures by using USArray data in USA. We extract broadband surface waves at 10-150 s from cross-correlation of ambient seismic noise and do Rayleigh wave phase velocity tomography from 10 s to 150 s. Using the resulting phase velocity maps, we construct a US 3D shear wave velocity model based on MCMC method. The 3D V_{sv} model constructed from broadband ANT here can provide strong constraints on structures from the surface to the asthenosphere.

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