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Layered structure in the upper mantle across North America from joint inversion of long and short period seismic data

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ABSTRACT

We estimate crustal and uppermost mantle shear velocity structure beneath 30 stations in North America by jointly inverting the high frequency scattered wavefield observed in the P wave coda, together with long period surface wave phase and group dispersion data. Several features distinguish our approach from previous such joint inversions. 1) We apply a cross-convolution method, rather than more standard deconvolution approaches used in receiver function studies, and consider both Love and Rayleigh wave dispersion, allowing us to infer profiles of radial anisotropy. 2) We generate probabilistic 1D radially anisotropic depth profiles across the whole uppermost mantle, down to ∼350 km depth. 3) The inverse problem is cast in a trans-dimensional Bayesian formalism, where the number of isotropic and anisotropic layers is treated as unknown, allowing us to obtain models described with the least number of parameters. Results show that the tectonically active region west of the Rocky Mountain Front is marked by a Lithospheric Asthenosphere Boundary and a Lehmann Discontinuity occurring at relatively shallow depths (60–150 km and 100–200 km, respectively), whereas further east, in the stable craton, these discontinuities are deeper (170–200 km and 200–250 km, respectively). In addition, in the stable part of the continent, at least two Mid-Lithospheric Discontinuities are present at intermediate depths, suggesting the existence of strong lithospheric layering, and a mechanism for lithospheric thickening by underplating of additional layers as cratonic age increases. The Moho across the continent as well as mid-crustal discontinuities in the craton are also imaged, in agreement with independent studies.

1. Introduction

Different seismological approaches have been used to image crustal and lithospheric structure at continental scales, in particular in North America (NA). At long periods (20–250 s), surface wave tomography provides resolution of volumetric heterogeneity down to ∼300 km depth, at scales down to ∼500 km laterally, and ∼50 km vertically (van der Lee and Frederiksen, 2005; Nettles and Dziewoński, 2008; Yuan et al., 2014; French and Romanowicz, 2014; Schaeffer and Lebedev, 2014). However, surface waves cannot uniquely resolve sharp interfaces, such as the Moho, the Lithosphere–Asthenosphere Boundary (LAB), the Lehmann discontinuity (L) or Mid-Lithospheric-Discontinuities (MLD's). In order to image such discontinuities, methods based on the analysis of the scattered wavefield at shorter periods (10–30 s) have been developed. The most frequently considered method uses information contained in phases converted at crust and upper mantle interfaces under single stations, the so-called receiver function method (RF, Vinnik, 1977; Ammon et al., 1990; Bostock, 1998).

The densification of broadband stations in NA (e.g. USArray) has made it possible to construct dense RF profiles across much of the conterminous US (e.g. Kumar et al., 2012; Hansen et al., 2015), confirming the first order striking differences in deep structure previously observed from tomography, between the tectonically active western US and the central craton (Marone and Romanowicz, 2007; Nettles and Dziewoński, 2008), with a rather sharp transition between them that roughly follows the Rocky Mountain Front (RMF, Fig. 1). West of this boundary, the crust is thinner, and a prominent negative boundary at depths between 60–80 km is generally interpreted as the LAB (Abt et al., 2010). East of this bound-

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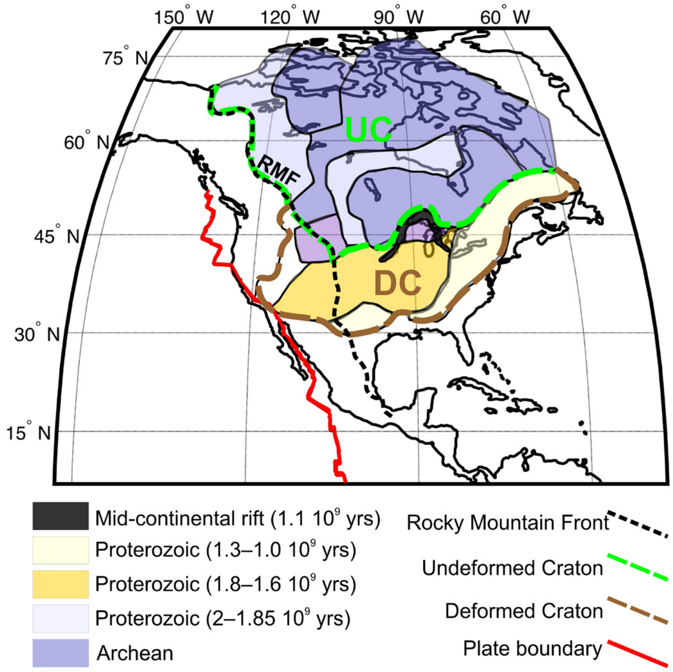

Fig. 1. Precambrian basement age in the North American continent simplified from Whitmeyer and Karlstrom (2007). Red line marks the plate boundaries and black dashed line indicates the Rocky Mountain Front (RMF). Green dashed line limits the undeformed craton (UC) and brown dashed one the deformed craton (DC). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

ary, the crust is thick, and the lithosphere reaches 200–250 km depth, as determined from global and continental scale seismic tomography. Moreover, anisotropic tomography combining long period waveforms with SKS splitting data has allowed the mapping of the LAB as a rapid change in the direction of the fast axis of anisotropy with depth, towards the absolute plate motion (APM) direction (e.g. Marone and Romanowicz, 2007; Yuan and Romanowicz, 2010). On the other hand, the LAB has not been detected consistently in the craton from RF studies, leading to its interpretation as a relatively gradual transition of primarily thermal nature (e.g. Abt et al., 2010), although recent studies based on USArray data seem to resolve it more clearly (Kumar et al., 2012; Hansen et al., 2015).

The presence of layering within the continental lithosphere has long been known (e.g. Hales, 1969) and confirmed from the analysis of long range seismic profiles, which showed the presence of a zone of scattering and lower seismic velocities starting at about 100 km depth in cratons, defining the so-called “8° discontinuity” (Thybo and Perchuc, 1997). Layering has also been found in scattering studies (e.g. Bostock, 1998) and the presence of negative discontinuities in the mid-lithosphere was clearly demonstrated in recent RF studies across the NA craton (Abt et al., 2010; Rychert et al., 2010; Kumar et al., 2012; Hansen et al., 2015). Interestingly, an MLD with large topographic variations in the depth range 100–160 km is detected by a rapid change in the fast axis direction of anisotropy (e.g. Yuan and Romanowicz, 2010).

At depths greater than 200 km, regional studies suggest the existence of additional reflectors such as the discontinuity discovered by Lehmann (1961). We refer to it as the “L” discontinuity in what follows. Generally, it is attributed to a petrologically distinct chemical boundary under continental cratons (Gu et al., 2001). Leven et al. (1981) suggest that the L corresponds to a change in the orientation of the fast axis of azimuthal anisotropy. However Vinnik et al. (2005) argue that seismic anisotropy plays a minor role in its origin.

The nature of the L, LAB and MLD(s) across NA remains a subject of vigorous debate, and different interpretations have been proposed as to their significance with respect to the formation of the cratonic lithosphere.

Although the RF approach provides information on fine-scale structure, this method presents several drawbacks: 1) lateral variations in the depth of discontinuities trades off with that of volumetric heterogeneity in the shallow mantle and crust (e.g. Ammon et al., 1990). Since the depth of discontinuities is generally determined through migration in a 1D earth model, their topography may be affected by unaccounted for velocity anomalies above them; 2) the imaged lithospheric discontinuities, especially in the case of P-to-s receiver functions, can be polluted by the strong signal from crustal reverberations, particularly in the depth of interest for continental lithospheric studies.

Since surface wave data and RFs provide complementary constraints on shallow earth structure, it is natural to try and combine them to obtain more robust models of the crust and uppermost mantle (e.g. Julià et al., 2000). This approach has recently gained momentum, in particular for constraining the depth of the Moho (e.g. Julià et al., 2000; Shen et al., 2013; Agrawal et al., 2015). Forward modeling approaches using a Monte Carlo Markov Chain (MCMC) framework (Sambridge and Mosegaard, 2002) have been developed for this purpose and applied in particular in NA (e.g. Shen et al., 2013), where the density of USArray stations combined with ambient noise tomography provides high-resolution 3D models of the crust and uppermost mantle.

In this work we apply a similar approach, albeit extended to a larger depth range, and jointly invert a combination of body wave data (scattered phases) and longer period surface wave dispersion data, in order to simultaneously investigate lateral variations in velocity and in the depth of upper mantle discontinuities in NA. There are several original aspects to our approach: 1) we consider both Love and Rayleigh wave dispersion data, allowing us to include radial anisotropy in our inversion; 2) instead of a standard RF methodology, our body wave dataset derives directly from seismic waveforms through a cross-convolution method (Bodin et al., 2014), avoiding the instabilities arising from deconvolution, and, importantly, allowing us to take into account crustal multiples without ambiguity; 3) we use a trans-dimensional MCMC approach in which the number of isotropic and anisotropic layers is treated as unknown, allowing us to obtain models with the least number of parameters compatible with the data (Bodin et al., 2014). In contrast to standard RF analysis, our approach allows us to constrain not only the position of discontinuities, but also the isotropic and anisotropic variations of shear velocity between them, in particular providing better constraints on the characteristics of the intra-lithospheric layers. Furthermore, the trans-dimensional parameterization allows us to account for the trade-off between layering, and radial anisotropy when jointly inverting Love and Rayleigh waves (Bodin et al., 2015).

Our forward modeling approach is based on a direct parameter search where a large number of Earth models are tested against the data, making it much more expensive computationally than standard RF migration schemes. Furthermore, increasing the period range of the surface waves data and the duration of the waveforms to investigate deeper structure also increases the computational burden with respect to other MCMC studies (e.g. Shen et al., 2013). It is therefore impractical to apply it to every single USArray station, at least for the moment. Instead, as a first step, we apply it to a subset of ∼30 selected stations that are representative of the large-scale lateral variations of structure in NA. In order to select the stations to represent contrasted structures across NA, we started from a recently developed high resolution global radially anisotropic shear velocity model of the mantle, to which we applied a cluster analysis method, to objectively define three distinct