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Lithospheric expression of geological units in central and eastern North America from full waveform tomography

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ABSTRACT

The EarthScope TA deployment has provided dense array coverage throughout the continental US and with it, the opportunity for high resolution 3D seismic velocity imaging of both lithosphere and asthenosphere in the continent. Building upon our previous long-period waveform tomographic modeling in North America, we present a higher resolution 3D isotropic and radially anisotropic shear wave velocity model of the North American lithospheric mantle, constructed tomographically using the spectral element method for wavefield computations and waveform data down to 40 s period. The new model exhibits pronounced spatial correlation between lateral variations in seismic velocity and anisotropy and major tectonic units as defined from surface geology. In the center of the continent, the North American craton exhibits uniformly thick lithosphere down to 200–250 km, while major tectonic sutures of Proterozoic age visible in the surface geology extend down to 100–150 km as relatively narrow zones of distinct radial anisotropy, with Vsv > Vsh. Notably, the upper mantle low velocity zone is present everywhere under the craton between 200 and 300 km depth. East of the continental rift margin, the lithosphere is broken up into a series of large, somewhat thinner (150 km) high velocity blocks, which extend laterally 200–300 km offshore into the Atlantic Ocean. Between the craton and these deep-rooted blocks, we find a prominent narrow band of low velocities that roughly follows the southern and eastern Laurentia rift margin and extends into New England. We suggest that the lithosphere along this band of low velocities may be thinned due to the combined effects of repeated rifting processes and northward extension of the hotspot related Bermuda low-velocity channel across the New England region. We propose that the deep rooted high velocity blocks east of the Laurentia margin represent the Proterozoic Gondwanian terranes of pan-African affinity, which were captured during the Rodinia formation but left behind after the opening of the Atlantic Ocean. Our results suggest that recurring episodes of tectonic events that are well exposed at the surface also leave persistent scars in the continental lithosphere mantle, marked by isotropic and radially anisotropic velocity anomalies that reach as deep as 100–150 km.

1. Introduction

Our knowledge of the upper mantle shear velocity structure beneath eastern and central North America (NA) has been limited due to the lack of dense seismic station coverage. This part of the NA continent has been subjected to less recent deformation than the southern and western borders, although it has been marked by several important episodes of tectonic events in the early history of the continent construction (Fig. 1(a)): the 1.92–1.77 Ga Trans-Hudson Orogeny, which represents plate collision between the Archean Wyoming, Hearn and Superior provinces, and is often compared to the present day Himalayas; the 1.71–1.68 Ga Yavapai and 1.70–1.65 Mazatzal orogenies, which correspond to the accretional addition of juvenile volcanic arcs to the cratonic core (Hoffman, 1988), and to the east, the 1.1 Ga Grenville and 260 Ma Appalachian orogenies, which correspond to the formation and breakup of supercontinents Rodinia and Pangea, respectively (Thomas, 2006).

In recent continental scale tomographic models, a thick cratonic root of fast shear velocity is imaged down to 200–250 km under the craton (e.g., Marone et al., 2007; Nettles and Dziewoński, 2008; Bedle and van der Lee, 2009; Yuan et al., 2011). While localized studies generally confirm this (e.g., Darbyshire and Lebedev, 2009; Chu et al., 2012; Frederiksen et al., 2013), rapid lateral changes in the velocity structure and thinning of the lithosphere have been observed towards the eastern continental margin (e.g., van der

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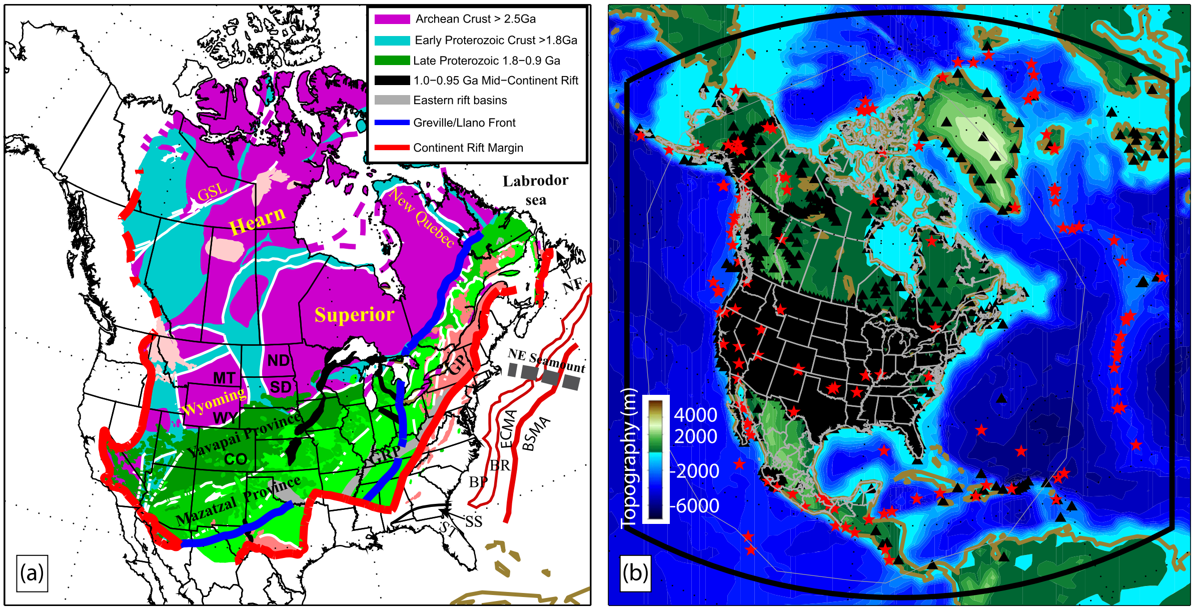

Fig. 1. (a) North American crustal provinces simplified from Whitmeyer and Karlstrom (2007). Archean and paleo-Proterozoic blocks are shaded in purple and blue in the north, while the series of southern Proterozoic provinces are shaded in green and pink. Thick red lines separate the continental core from exotic accretionary terranes. The thick blue line follows the Grenville/Llano deformation front. White lines show sutures/thrust faults. Labels are: BK, Blake Plateau; BR, Blake Ridge; BSMA, Blake Spur Magnetic Anomaly; ECMA, East Coast Magnetic Anomaly; GP, Grenville Province; GRP, Granite/Rhyolite Province; GSL, Great Slave Lake suture; NE Seamount, New England Seamount; NF, New Foundland; SS, Suwannee Suture; and ST, Suwannee Terrane. State abbreviations are: CO, Colorado; MT, Montana; ND, North Dakota; SD, South Dakota; and WY, Wyoming. (b) Source and station distribution for the new North American inversion. Black triangles show the seismic stations. Red stars are 136 local events which contribute to the new 40 s waveforms in addition to our 60 s global (French et al., 2013) and North American dataset (Yuan et al., 2011). Thick black line indicates the boundaries used for the RegSEM forward simulation, which extends 89° by 89° horizontally and down to 1600 km and contains all event-to-station paths in the 40 s dataset. The thin gray polygon indicates our model region in which the Vs and ξ structure is determined. Background shows the topography. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Lee and Nolet, 1997; Levin et al., 2000; Rondenay et al., 2000; Menke and Levin, 2002; Li et al., 2003; Frederiksen et al., 2013). The uniquely dense coverage of the EarthScope Transportable Array (TA) in the central and eastern US opens up the opportunity to image upper mantle velocity structure at unprecedented resolution from coast to coast, which helps further our understanding of the tectonic history of the North American continent, i.e. the process of assembly of the craton and subsequent reworking of its borders. Here we show that the signature of distinct tectonic events preserved in the crust is also present in the lithospheric upper mantle down to depths reaching 150 km or more.

In this study, we present a new high-resolution 3D tomographic model of shear velocity and radial anisotropy in the cratonic North American mantle, developed using long-period full waveform inversion. This study builds upon our previous continental scale tomographic modeling efforts (Marone et al., 2007; Marone and Romanowicz, 2007; Yuan and Romanowicz, 2010b; Yuan et al., 2011). A salient feature of our previous models is the definition of the lithosphere–asthenosphere boundary (LAB) based on the variation with depth of azimuthal anisotropy: in the NA craton, the fast velocity axis changes direction towards the present day absolute plate motion direction below a depth of 180–240 km. Above the LAB the anisotropy is therefore "frozen-in" in the lithosphere, which moves as a whole over the presently deformed asthenosphere. This transition in anisotropy corresponds to a zone of strong negative gradient in isotropic shear velocity, which, however, occurs over a depth range that is too wide to be detected by high frequency methods sensitive to sharp discontinuities, such as P and S wave receiver functions and SS precursors. Further exploring the depth variations of the LAB, and better constraining the absolute values of shear velocities in the lithospheric layers is therefore a worthy goal as the Transportable Array progresses towards the eastern edge of the continent.

2. Tomographic inversion: data and methodology

The new inversion shares many methodological features with our previous continental scale time-domain three-component waveform tomographic inversions for isotropic and radially anisotropic structure (Marone et al., 2007; Yuan et al., 2011). Readers are referred to previous papers (Marone et al., 2007; Yuan et al., 2011) for the theoretical background of the regional waveform tomographic inversion methodology. Below, we highlight significant aspects of the new regional inversion.

Similar to previous inversions, the regional model is embedded in an existing global tomographic model, which serves to correct waveforms for 3D structure effects outside of the region studied. Here the global model considered is the most recent global radially anisotropic shear velocity model, SEMum2 (French et al., 2013), a second generation high resolution waveform-based model of the upper mantle developed using the spectral element method (SEM). In our previous regional studies, only teleseismic records were used, and the records were low-pass filtered at 60 s. Observed waveforms were partitioned into wave packets, allowing us to assign equal weights to fundamental modes and overtones. These wavepackets were then compared to synthetics computed using non-linear asymptotic coupling theory (NACT; Li and Romanowicz, 1995), a method based on normal mode perturbation theory which includes across branch mode coupling, resulting in 2D finite frequency waveform kernels in the vertical plane containing the source and the receiver.

Here, in addition to the 60 s low-pass filtered waveform data from ∼360 global events observed on global seismic networks (used in French et al., 2013; referred to as "the 60 s global dataset") and ∼600 global events observed at NA stations (used in Yuan et al., 2011; referred to as "the 60 s NA dataset"), we further include waveforms from 136 North American regional events (Fig. 1(b)) which surround our study area (including TA stations