Earth and Planetary Science Letters 489 (2018) 8–16

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Seismic attenuation in the African LLSVP estimated from PcS phases

Chujie Liu*, Stephen P. Grand

Department of Geological Sciences, Jackson School of Geosciences, The University of Texas at Austin, Austin, TX 78712, USA

ARTICLE INFO

Article history:
Received 5 December 2017
Received in revised form 12 February 2018
Accepted 20 February 2018
Available online xxxx
Editor: P. Shearer

Keywords:
seismic attenuation
LLSVP
body wave
mantle heterogeneity

ABSTRACT

Seismic tomography models have revealed two broad regions in the lowermost mantle marked by ∼3% slower shear velocity than normal beneath the south central Pacific and southern Africa. These two regions are known as large-low-shear-velocity provinces (LLSVP). There is debate over whether the LLSVPs can be explained by purely thermal variations or whether they must be chemically distinct from normal mantle. Elastic properties alone, have been unable to distinguish the thermal from chemical interpretations. Anelastic structure, however, can help discriminate among models of the LLSVPs since intrinsic attenuation is more sensitive to temperature than to chemical variations. Here we estimate Q_μ (the shear wave quality factor) in the African LLSVP using PcS waves generated from a Scotia Arc earthquake, recorded by broadband seismometers deployed in Southern Africa during the Kaapvaal experiment. The upward leg of the PcS waves sweeps from normal mantle into the African LLSVP across the array. We use the spectral ratio (SR) and instantaneous frequency matching (IFM) techniques to measure the differential attenuation (Δt^*) between waves sampling the African LLSVP and the waves that sample normal lower mantle. Using both methods for estimating Δt^* we find that PcS waves sampling the LLSVP are more attenuated than the waves that miss the LLSVP yielding a Δt^* difference of more than 1 s. Using the Δt^* measurements we estimate the average Q_μ in the LLSVP to be about 110. Using a range of activation enthalpy (H^*) estimates, we find an average temperature anomaly within the LLSVP ranging from +250 to +800 K. Our estimated temperature anomaly range overlaps previous isochemical geodynamic studies that explain the LLSVP as a purely thermal structure although the large uncertainties cannot rule out chemical variations as well.

1. Introduction

Global seismic tomography has made great progress over the past 30 yr or so, with most models in agreement on the long wavelength heterogeneity in the mantle. Two prominent features common in the models are large slow shear velocity structures beneath the south-central Pacific and Southern Africa (French and Romanowicz, 2015; Lu and Grand, 2016; Masters et al., 1996; Ritsema et al., 1999). The structures have come to be known as the Pacific Large-Low-Shear-Velocity Province (LLSVP) and the African LLSVP. The LLSVPs are marked by roughly 3% slower shear velocity than normal mantle with less than 1% P wave anomalies (Koelemeijer et al., 2015). The African anomaly is a dome-like structure that extends laterally for over 2000 km, from beneath the southeastern Atlantic Ocean to the southwestern Indian Ocean, and reaches up to about 1000 km depth (Durand et al., 2017). The Pacific anomaly has several separated small-scale piles embedded in the LLSVP, which is about 2000 km wide and 500 km height (Garnero et al., 2016).

Understanding the nature of the LLSVPs is critical to understand the evolution and dynamics of the lower mantle. The location of hotspots and large igneous province eruption sites have been correlated with the edges of the LLSVPs (Thorne et al., 2004; Torsvik et al., 2006), showing a connection between them and surface phenomena. Furthermore, Montelli et al. (2006) and French and Romanowicz (2015) have shown continuous slow seismic anomalies from the LLSVPs in the deepest mantle to the upper mantle roughly correlated with surface hotspots. A fundamental question concerning the LLSVPs is whether they are largely due to thermal perturbations or whether they are chemically distinct from the surrounding mantle. Ishii and Tromp (1999), using normal mode splitting, found the density is anomalously high within the African LLSVP implying that the African LLSVP is chemically distinct from normal mantle. Trampert et al. (2004) also found an anti-correlation between shear velocity and density in the deepest mantle. Kuo and Romanowicz (2002), however, determined that normal mode data cannot resolve lateral density anomalies. Recently, Koelemeijer et al. (2017), using Stoneley Modes, found the

---

* Corresponding author.
E-mail address: lcj2012@utexas.edu (C. Liu).

https://doi.org/10.1016/j.epsl.2018.02.023

African LLSVP to be relatively buoyant in contradiction to the results of Ishii and Tromp (1999).

Sharp boundaries of the LLSVPs (Ni et al., 2002; Sun et al., 2009) as well as an apparent anti-correlation of bulk sound speed and shear wave velocity in the deep lower mantle (Masters et al., 2000; Trampert et al., 2004) have been used to argue for chemically distinct LLSVPs. Geodynamic modeling of thermochemical piles in the lower mantle (Davaille et al., 2002; McNamara and Zhong, 2005; Steinberger and Torsvik, 2012) have been successful in explaining the morphology of the LLSVPs. However, Schuberth et al. (2009a, 2012), and Davies et al. (2012) have argued that the seismic observations can be largely explained by purely thermal convection without the need for chemical anomalies within the LLSVPs. Furthermore, Simmons et al. (2009) and Tesoniero et al. (2016) have shown that the P to S velocity ratio in the deep mantle is difficult to resolve.

Although there have been great advances in observational constraints of the elastic properties of the LLSVPs, their thermochemical properties are still controversial. Much less is known about the anelastic properties of the LLSVPs. Knowledge of the Q structure of the lower mantle can provide different constraints on the nature of the LLSVPs. This is because, compared to elastic velocities, intrinsic attenuation is more sensitive to temperature and is likely less sensitive to chemical composition (Matas and Bukowinski, 2007; Romanowicz, 1995). However, mantle Q structure is more difficult to measure than elastic velocities. One dimensional models of Q have been determined using normal mode and surface wave data (PREM from Dziewonski and Anderson, 1981; model QL6 from Durek and Ekström, 1996) and body wave data (model QOS08, Oki and Shearer, 2008; model QHR12, Hwang and Ritsema, 2011; model QLM9, Lawrence and Wysession, 2006; Durand et al., 2013). The frequency range of these body wave studies are typically about 0.02–0.2 Hz for measuring ScS/S and 0.1–0.8 Hz for measuring teleseismic P and S waves, while normal node and surface wave based studies use data with periods often greater than 150 s. These models show a range of average lower mantle Q_μ from about 300–600. The spread may be due to frequency dependence of Q_μ, that is still not well determined, as well as the intrinsic difficulty in measuring Q.

Three dimensional variations of mantle Q are, of course, less well mapped than the average Q. Upper mantle tomographic Q_μ models have been developed using surface wave amplitudes (Adenis et al., 2017; Dalton et al., 2008; Romanowicz, 1995) and body wave data (Bhattacharyya et al., 1996; Warren and Shearer, 2002) but there has been less success mapping 3D variations in Q_μ in the lower mantle. Using teleseismic P and S wave spectral ratios (up to 0.8 Hz), Hwang and Ritsema (2011) found that the Pacific LLSVP has at most 17% lower Q_μ than beneath the surrounding circum-Pacific. Through 1-D waveform inversion of S and ScS waves, Konishi et al. (2016) found a Q_μ of 216 at the bottom of the Caroline plume in the Pacific LLSVP, which is 30% lower than PREM. The amplitude decay of ScS reverberations has also been used to investigate lower mantle Q_μ (Kanamori and Rivera, 2015; Kovach and Anderson, 1964; Sipkin and Jordan, 1980) although Chaves and Ritsema (2016) found that velocity heterogeneity can strongly influence the results using this method. They calculate synthetic waveforms for 3D tomography models and show that focusing and scattering caused by long-wavelength heterogeneity in the mantle can produce variable multiple ScS amplitude ratios.

In this study we use a unique data set of PcS waves to investigate the difference in Q_μ between the African LLSVP and the surrounding lower mantle. The data come from a Scotia Islands earthquake recorded by a temporary array of seismometers in Southern Africa. Some of the PcS waves from this event propagate through the African LLSVP while another group do not. We measured the differential attenuation (Δt^*) between these groups using two methods to place constraints on the difference in Q_μ within the African LLSVP relative to outside it. The next section discusses the data in more detail followed by a discussion of the techniques we used.

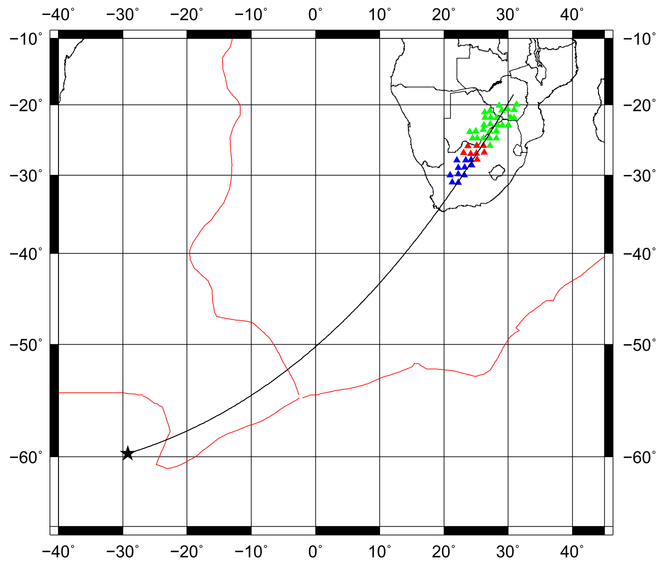

Fig. 1. Location of the earthquake (star) and the stations (triangles) used in the study. Red lines are the locations of plate boundaries, and the black curve is the location of the cross-section shown in Fig. 3. The stations are divided into three groups, discussed in the text, and are labeled by different colors. Blue stations are in group 1, red in group 2, and green in group 3.

2. Data and pre-processing

From 1997 to 1999, 80 broadband three-component seismometers were deployed across Southern Africa as part of the Kaapvaal experiment (Silver, 1997). We searched for earthquakes located in the Scotia Arc that showed clear core phases recorded by the Kaapvaal array. A unique event, on October 5, 1997, produced clear PcS (a wave that travels to the core as P and reflects to the surface as S) recordings across Southern Africa. Fig. 1 shows the location of the event as well as the locations of the seismic stations used in this study. We deconvolved the instrument responses, removed the mean and linear trend from the signals and applied a second order Butterworth bandpass filter with frequency passband 0.02–0.3 Hz to the data. Fig. 2 shows the processed displacement data. Note the clear PcS arrivals on the radial component across the array. The vertical component seismograms (Fig. 2b) show clear PcP waves at the larger distances but this phase crosses the sP phase at shorter distances. The travel time curves in Fig. 2 are computed using the PREM model (Dziewonski and Anderson, 1981). Fig. 2c shows a close-up of the PcS arrivals aligned according to the predicted time using the PREM model. Note that the delay time of PcS relative to the PREM prediction is greater at large offsets compared to closer distances.

The PcS waves sample the African LLSVP in a fortuitous way. Fig. 3 shows a cross section through the S-wave tomography model TX16 of Lu and Grand (2016) with the raypaths of the PcS waves calculated assuming the PREM velocity model (Dziewonski and Anderson, 1981). The location of the cross section is shown in Fig. 1 (black curve). The raypaths were projected onto the cross section but the seismic array is closely aligned with the section such that projection onto the line gives very little error. For this tomography model, the PcS waves at large distances pass through the slow velocity African LLSVP but at shorter distances they miss the slow region. Fig. 3 also shows the raypaths of the S waves. Note, the S waves do not encounter any significant slow anomalies. We