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Absence of thermal influence from the African Superswell and cratonic keels on the mantle transition zone beneath southern Africa: Evidence from receiver function imaging

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ABSTRACT

The depths of the 410 km (*d*410) and 660 km (*d*660) discontinuities beneath southern Africa, which is presumably underlain by the lower-mantle African Superswell, are imaged in 1° radius consecutive circular bins using over 6400 *P*-to-*S* receiver functions (RFs) recorded by 130 seismic stations over a 27 yr period. When the IASP91 standard Earth model is utilized for moveout correction and time-depth conversion, a normal mantle transition zone (MTZ) thickness of 246 ± 7 km is observed, suggesting that the Superswell has no discernible effect on mantle transition zone temperature. Based on the negligible disparity of the mean MTZ thicknesses between on (246 ± 6 km) and off (246 ± 8 km) cratonic regions, we conclude that the deep Archean cratonic keels possess limited influence on MTZ thermal structure. The apparently shallower-than-normal MTZ discontinuities and the parallelism between the *d*410 and *d*660 are mostly the results of upper mantle high wave speed anomalies probably corresponding to a thick lithosphere with a mean thickness of about 245 km beneath the Kaapvaal and 215 km beneath the Zimbabwe cratons. In contradiction to conclusions from some of the previous studies, the resulting spatial distribution of the stacking amplitudes of the *P*-to-*S* converted phases at the discontinuities is inconsistent with the presence of an excessive amount of water in the MTZ and atop the *d*410.

1. Introduction

In spite of numerous observational and geodynamic modeling studies, mechanisms responsible for the anomalously high topography of southern Africa (Fig. 1) remain controversial (Lithgow-Bertelloni and Silver, 1998; Hu et al., 2018). One of the most commonly invoked hypotheses is the dynamic effects of the African Superswell, a low-seismic wave speed anomaly in the lower mantle beneath most of the southern hemispheric region of Africa and the neighboring oceanic areas of the African Plate (Lithgow-Bertelloni and Silver, 1998; Romanowicz and Gung, 2002; Ni et al., 2005). Whether the presumably high temperature from the Superswell has influenced the structure and deformation (especially rifting) of the upper mantle and mantle transition zone (MTZ), a layer of the Earth sandwiched between the 410 km (*d*410) and 660 km (*d*660) discontinuities, is still a debated subject (Ritsema et al., 1998; Priestley et al., 2008; Fishwick, 2010; Youssof et al., 2015). Another controversial issue is the depth extent of the cratonic keels and their influence on the temperature distribution in the upper mantle and MTZ. Beneath the Kaapvaal and Zimbabwe cratons, seismic surface wave studies suggested a lithospheric thickness of 160–250 km (Li and Burke, 2006; Chevrot and Zhao, 2007; Priestley et al., 2008; Schaeffer and Lebedev, 2013), while other studies especially those using teleseismic body-waves (James et al., 2001; Youssof et al., 2015) revealed a much thicker lithosphere, down to about 300 to 350 km, which may cause low temperature anomalies in the MTZ (Blum and Shen, 2004). The discrepancy is most likely caused by the limited resolving power and the consequent large uncertainties in the tomographic methods. Body-wave tomographic techniques pervasively utilize relative (rather than absolute) travel time residuals and thus the resulting wave speed anomalies are relative to the mean over the region investigated (Foulger et al., 2013). Additionally, they suffer from vertical smearing due to the steep ray paths beneath the station. In contrast, surface-wave tomographic techniques produce absolute wave speed anomalies, and have inherently better vertical resolution but poorer horizontal resolution due to lateral smearing.

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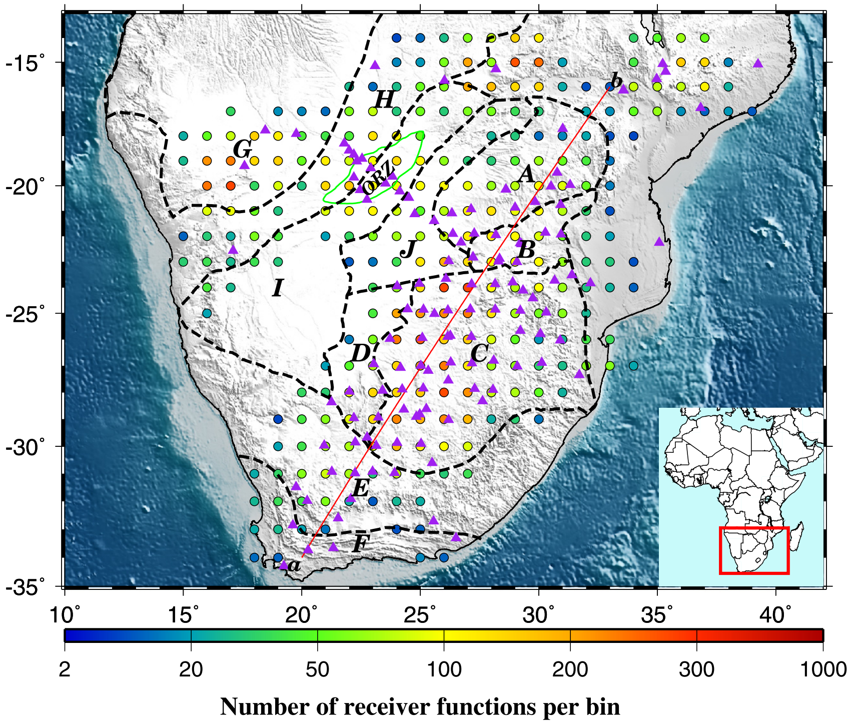

Fig. 1. Topographic relief map of the study area showing the center of radius = 1° bins (filled circles), and major tectonic boundaries (black dashed lines). The color of the circles represents the number of the RFs per bin. The purple triangles are seismic stations used in the study. The subareas include: A: Zimbabwe Craton; B: Limpopo Belt; C: Kaapvaal Craton; D: Kheiss Belt; E: Namaqua–Natal Belt; F: Cape Fold Belt; G: southern Congo Craton; H: Damara Belt; I: Rehoboth Province; J: Magondi Belt. Line a–b indicates the location of the profile shown in Fig. 8. The red rectangle in the inset map shows the study area. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

It has long been recognized that the topography of the *d*410 and *d*660 can provide independent constraints on the thermal and wave speed structures of the upper mantle and MTZ (Anderson, 1967; Flanagan and Shearer, 1998). The discontinuities reflect sudden changes in mineralogical phases, from olivine to wadsleyite at the *d*410, and from ringwoodite to bridgmanite at the *d*660 (Ringwood, 1975). Due to the opposite sign of the Clapeyron slopes (ranging from +1.5 MPa/K to +4.0 MPa/K for *d*410 and from −0.2 MPa/K to −4.0 MPa/K for *d*660; Tauzin and Ricard, 2014), high and low temperature anomalies can result in a thinner-than-normal and thicker-than-normal MTZ, respectively. In addition, the existence of water-saturated minerals in the MTZ could thicken the MTZ (Litasov et al., 2005), and an excessive amount of water tends to broaden the interval of the olivine–wadsleyite phase transition and reduce the sharpness of the *d*410 (Wood et al., 1996; Smyth and Frost, 2002; van der Meijde et al., 2003). Therefore, variations of the depths and sharpness of the *d*410 and *d*660 are effective indicators of spatial variations of thermal perturbations and water content anomalies in the vicinity of the MTZ discontinuities (Ringwood, 1975).

Several MTZ studies have been conducted in southern Africa with controversial conclusions. Gao et al. (2002) estimated an MTZ thickness of 245 km that is comparable to the global average, and suggested that the lower-mantle African Superswell beneath southern Africa has no observable influence on the MTZ temperature. In contrast, Blum and Shen (2004) detected a 20 km thicker-than-normal MTZ beneath the Archean cratons in southern Africa, and interpreted it as the consequence of the extension of low-temperature, water-saturated Archean cratonic keels to the base of the MTZ. Another MTZ study (Niu et al., 2004) showed a normal MTZ thickness and suggested that the highly depleted root causes an approximately 20 km apparent uplift of the *d*410 and *d*660 relative to the global average beneath the Kaapvaal craton. Julia and Nyblade (2013) utilized 2557 *P*-to-*S* receiver functions (RFs) from 30 permanent broadband stations in Africa, including 7 stations in our study area (Fig. 1), to image the MTZ discontinuities. They reported *d*410 depths in the range of 405 ± 10 km, and *d*660 depths of 655 ± 11 km with a mean MTZ thickness of 250 ± 3 km beneath southern Africa. A recent MTZ study across the Okavango Rift zone conducted by Yu et al. (2015) revealed apparently shallower-than-normal MTZ discontinuities beneath the northern Kalahari Craton and a normal MTZ thickness beneath most of the study area, suggesting the absence of mantle plumes beneath the incipient rift.

The discrepancies in the results and conclusions from previous MTZ studies in southern Africa (Gao et al., 2002; Shen and Blum, 2003; Blum and Shen, 2004; Niu et al., 2004) are mostly the results of the limited amount of seismic data and the different methodologies applied by different research groups. In this study, we apply a non-plane wave assumption approach (Gao and Liu, 2014a) to an expanded data set recorded over the past 27 yr to provide an enhanced image of the MTZ discontinuities beneath southern Africa. Relative to methodologies based on the plane-wave assumption, our approach can lead to sharper MTZ discontinuity arrivals and more accurately determined depths (Gao and Liu, 2014a). In addition to the unprecedented number of high quality RFs used in this study, the spatial coverage is more extensive than the aforementioned regional-scale studies. The results provide tighter and more reliable constraints on the deep structure and temperature and water content of the upper mantle and MTZ beneath two of the oldest cratons on Earth, and the only continental area that is presumably underlain by a lower-mantle superswell.