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Key Points:
- Thick crust, high V_p/V_s ratios is found at the landfall of the Walvis Ridge
- Evidence for magmatic underplating beneath the African continental crust
- The extension of the plume area of influence is less than 300 km in diameter

Supporting Information:
- Table S1

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Crustal thickness and V_p/V_s ratio in NW Namibia from receiver functions: Evidence for magmatic underplating due to mantle plume-crust interaction

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Abstract A seismological network was operated at the junction of the aseismic Walvis Ridge with the northwestern Namibian coast. We mapped crustal thickness and bulk V_p/V_s ratio by the H-k analysis of receiver functions. In the Damara Belt, the crustal thickness is ~35 km with a V_p/V_s ratio of <1.75. The crust is ~30 km thick at the coast in the Kaoko Belt. Strong variations in crustal thickness and V_p/V_s ratios are found at the landfall of the Walvis Ridge. Here and at ~150 km northeast of the coast, the crustal thickness increases dramatically reaching 44 km and the V_p/V_s ratios are extremely high (~1.89). These anomalies are interpreted as magmatic underplating produced by the mantle plume during the breakup of Gondwana. The area affected by the plume is smaller than 300 km in diameter, possibly ruling out the existence of a large plume head under the continent during the breakup.

1. Introduction

The Parana-Etendeka is a large continental flood-basalt province located in both continents South America and Africa, which is associated with the opening of the South Atlantic Ocean during the breakup of the Gondwana continents at ~130 Ma. Post-rift-offshore volcanism is manifested by a large submarine plateau, the Rio Grande Rise off Brazil, the aseismic Walvis Ridge off Namibia, and finally the recent volcanism at the Tristan da Cunha island located close to the mid-ocean ridge (Figure 1).

The mantle plume hypothesis has been used to explain the existence of the conjugated flood basalt provinces on both sides of the South Atlantic Ocean. Furthermore, the age progression of gredged/drilled basaltic rocks along the 3000 km long Walvis Ridge might have been caused by a plume-lithosphere interaction [*O'Connor and Duncan*, 1990]. However, a deep-rooted low-velocity anomaly, i.e., a typical seismic characteristic of a mantle plume, has not been observed in the deep mantle beneath Tristan da Cunha (TdC) by global tomography studies [*Ritsema and Allen*, 2003; *Montelli et al.*, 2004]. Other theories reject the necessity of a mantle plume to produce a volcanic aseismic chain [e.g., *Fairhead and Wilson*, 2005]. They interpret the development of the Walvis Ridge as a result of deformational processes during the evolution of the plates and suggest that periodical stress release in the form of shear and wrench displacement caused localized decompression melting of the mantle resulting in short volcanic lineaments. Thus, the moving volcanic centers are the response to the reactivation of the lineaments when the stresses in the oceanic plate have become too big where the lithosphere has already been weakened by the previous displacement. This theory could also explain the asymmetric geometry of the Walvis Ridge and its counterpart the Rio Grande Rise and the apparently double volcanic chain developed along the track of the Walvis Ridge as a result of induced oceanic crust weakness.

The Walvis Ridge intersects the African continent in northwest Namibia, one of the key areas to study the ridge-lithosphere interaction. The area lacks local seismological information and has only been investigated by a small number of studies involving controlled-source seismic experiments [*Bauer et al.*, 2000, 2003] and global teleseismic studies [*Ritsema and Allen*, 2003; *Sebai et al.*, 2006]. *Bauer et al.* [2000] observed high velocities within the continent-ocean transitional crust offshore Namibia and interpreted it as magmatic underplating. Tomographic studies by *Sebai et al.* [2006] and recently by *Colli et al.* [2013] show velocity variations in the upper mantle on the eastern Atlantic ocean. The scale of these

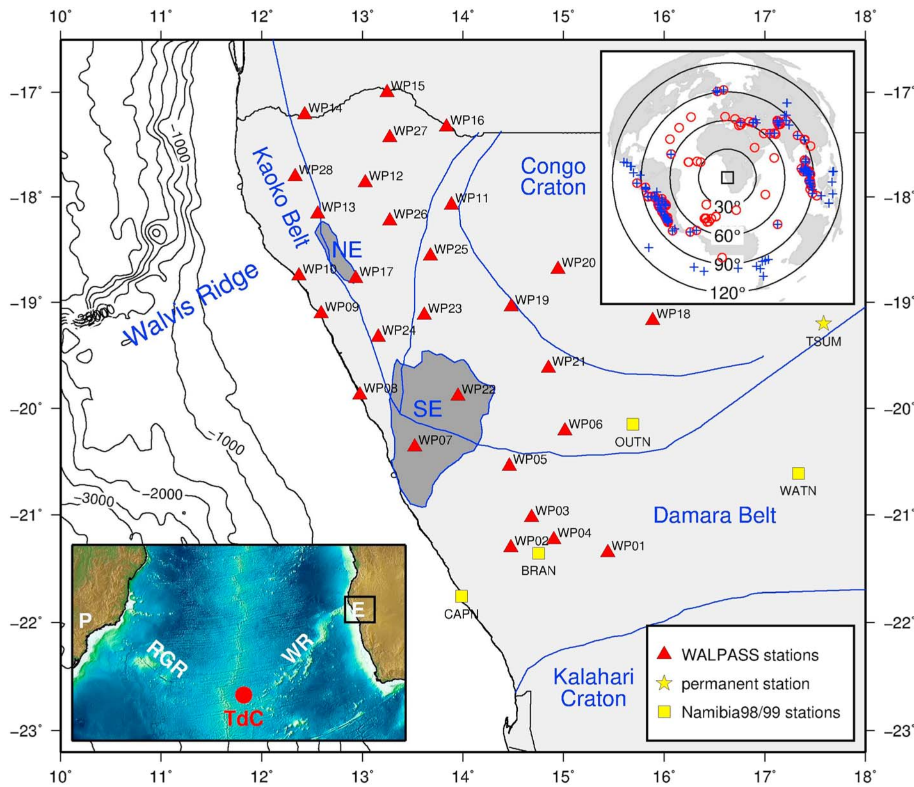

Figure 1. Map of stations used in this study with bathymetric contours at an interval of 500 m (black solid lines) and simplified tectonic features (blue solid lines) from *Milner and Le Roex* [1996]. SE and NE indicate Southern and Northern Etendeka flood basalts, respectively. The lower left inset shows the Southern Atlantic Ocean with indication of the Tristan da Cunha hot spot (TdC), the Walvis Ridge (WR), and the Rio Grande Rise. P and E denote Parana and Etendeka flood basalt provinces, respectively. The black square marks the study area. The upper right inset shows the teleseismic events used for calculation of the *P* and *S* receiver functions, denoted by red circles and blue crosses, respectively.

tomographic images is although not adequate for investigating the Walvis region. All previous studies lack information on crustal/lithospheric thicknesses of the continent-ocean transition zone following continental breakup.

We conducted a passive source seismological experiment aiming to study the seismic structure of the crust and mantle lithosphere by a number of seismic methods including receiver functions, body and surface wave tomography, shear wave splitting, and local earthquake analysis. The experiment has been designed to provide constraints on any crustal modification caused by plume-lithosphere interaction at the initiation of a plume track. Here we present the crustal thickness and V_p/V_s ratios obtained for in NW Namibia from receiver functions.

The study area includes parts of the Congo Craton in the north, the Kaoko mobile belt in the west, and the Damara Belt in the south (Figure 1). The Neoproterozoic Damara orogen in Namibia records the Gondwana assembly of the Congo-Kalahari-Rio de la Plata (in South America) Cratons [*Prave*, 1996]. In this context, the Damara mobile belt developed as a result of the closure of an ocean basin at 550 Ma between the Congo Craton in the north and the Kalahari Craton in the south. This region has been recognized to have a composite origin (i.e., the Congo Craton is thought to be formed by several Archean shields as the Angolan shield in the south [see *Khoza et al.*, 2013, and references therein]) and the collision with the Kalahari Craton during the Gondwana continental assemblage [*Prave*, 1996]. The Kaoko Belt is one of the coastal arms of the Damara Orogen and consists of deformed rocks of Neoproterozoic age [*Begg et al.*, 2009]. The Congo Craton is composed of different terranes of Archean age with no clear identified boundaries so far toward the Damara and Kaoko Belts and is mostly represented by rocks composing the Angolan Shield at the southwestern border of the craton

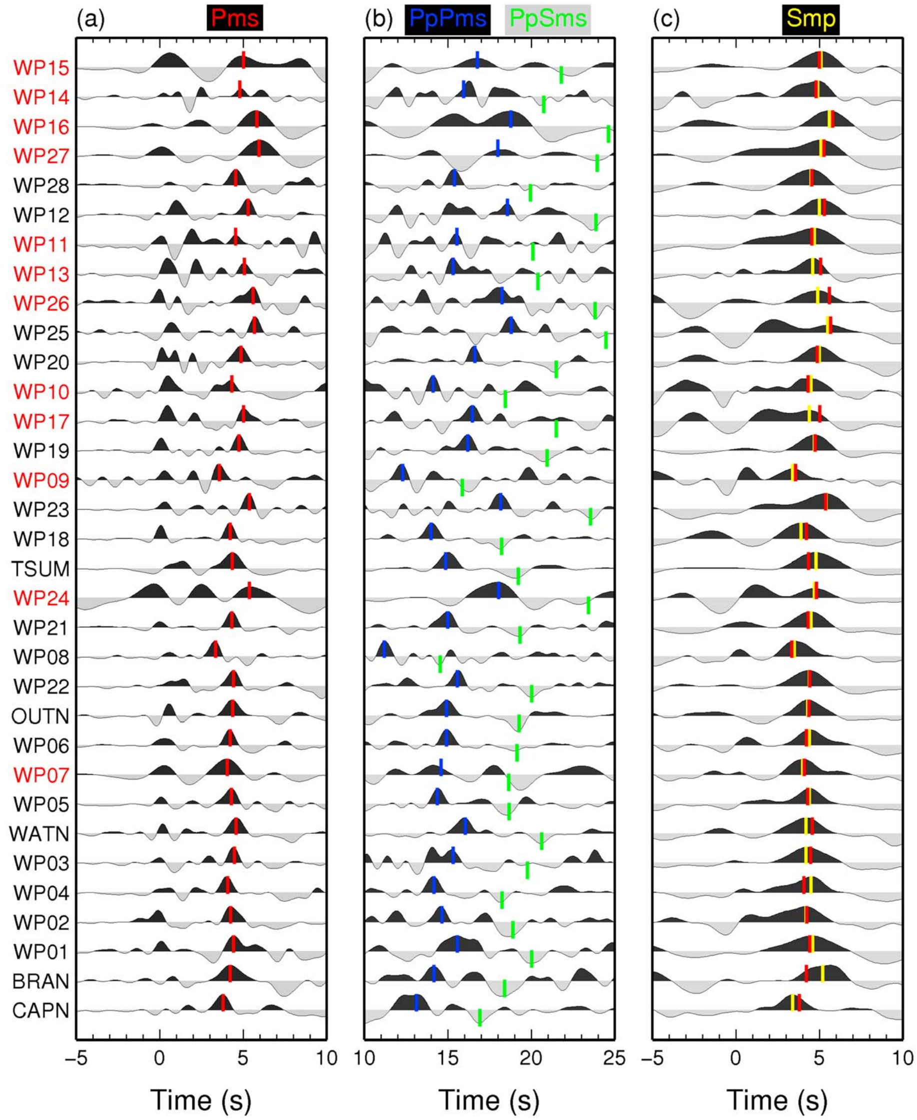

Figure 2. Stacked receiver functions for each station with moveout corrections applied for (a) *Ps*, (b) *PpPs*, and (c) *Sp*. The moveout for *PpSs* is almost identical as that for *PpPs*. A low-pass filter of 3 s is applied to stations WP07, WP15, WP16, WP24, and WP27 to enhance the multiples. Amplitudes are normalized to each trace within the time window. The red ticks in Figure 2a and the blue and green ticks in Figure 2b mark the times of Moho phases of *Pms*, *PpPms*, and *PpSms*, respectively, derived by the H-k analysis. The red and yellow ticks in Figure 2c indicate the times of Moho phases of *Pms* and *Smp*. The red station codes indicate the stations with weak or complicated *Pms*.

[*Begg et al*., 2009]. At the border with Angola in the north of the study area, the Kunene and Epupa complexes with a strong mafic-ultramafic components are among the oldest rocks in Namibia [*Schneider et al*., 2008].

The seismic network consists of 28 stations operated for 2 years in northwest Namibia between November 2010 and November 2012. A permanent station in Tsumeb and a small GEOFON temporary experiment (operated between 1998 and 1999) provide additional data (Figure 1). Here we report on receiver function analysis of the crustal structure and show anomalies related to the Walvis Ridge in northern Namibia. As a part of the amphibian seismic experiment, 12 ocean-bottom seismographs were deployed offshore Namibia. However, they failed to provide constraints on crustal thickness since the strong *P*-to-*S* conversion at the base of sediments masks arrivals from the crust-mantle boundary. These stations are therefore not included in this study.

2. Data and Methodology

We performed a teleseismic *P* and *S* wave receiver function study (PRF and SRF, respectively) using events from the National Earthquake Information Center catalog that were recorded at epicentral distances between 30° and 95° for PRF and between 60° and 85° for SRF (including also *SKS* phase at epicentral distances of 85°–115°, also referred to here as SRF).

For both PRF and SRF, the magnitudes (mb) are greater than 5.5. The events used are shown in Figure 1. The PRF computation was performed following the approach described by *Yuan et al*. [1997], whereas the SRF analysis was performed using the approach by *Kumar et al*. [2006] and *Yuan et al*. [2006]. Signal-to-noise ratios have been visually inspected, and the traces were manually selected for calculation of *P* and *S* receiver functions. The traces were rotated, deconvolved, and moveout corrected for a reference slowness of 6.4 s/deg. We obtained 2000 *P* and 1300 *S* receiver functions.

3. Results

In Figure 2 we present the stacked *P* and *S* receiver functions at each station after moveout correction for *Ps* (Figure 2a), *PpPs* (Figure 2b), and *Sp* (Figure 2c), in order to enhance the corresponding converted phases. The *Pms* and *Smp* phases are directly converted *P*-to-*S* and *S*-to-*P* phases at the Moho, while the *PpPms* and *PpSms* phases are multiple reverberations between the Moho and the surface. In each figure, stations are sorted from south to north. The Moho phase (*Pms*) is well recognized at almost all stations by the independent phases, indicated by red colored ticks in the figure. The *Pms* phase is clear and simple with clear multiples for stations located in the south (i.e., approximately south of 19°S), suggesting a simple crustal structure. At many stations in the north (at the landfall of Walvis Ridge), the *Pms* becomes either weaker (e.g., WP11 and WP15), broader (e.g., WP26 and WP16), or shows multiple picks (e.g., WP10, WP26, WP27, WP14, and WP15). The multiples are not as clear as at the stations in the south and are invisible at some stations at high frequency (e.g., WP16 and WP15). At five stations (WP07, WP15, WP16, WP24, and WP27), a low-pass filter of 3 s was applied to enhance the amplitudes of the multiples. This may suggest that the crust there has a complicated structure with a gradual or multiple-velocity contrast at the Moho. The long-period *S* receiver functions are less influenced by the complicated Moho contrast and therefore provide robust additional constraints on the Moho depth (Figure 2c).

We use the H-k stacking approach [*Zhu and Kanamori*, 2000] to estimate the crustal thickness and the average V_p/V_s ratio. Here we chose for most of the stations unequal weights of 0.6, 0.3, and 0.1 for *Pms*, *PpPms*, and *PpSms* phases, respectively. In a few cases we slightly adjusted the weighting depending on the signal-to-noise ratios. In Figure 3 we present sample receiver functions and the H-k analysis for two stations. Stations WP04 is located in the south at the Damara Belt. Clear Moho can be identified by *Pms*, *PpPms*, and *PpSms* phases in the *P* receiver functions (Figure 3a) and the *Smp* phase in the *S* receiver functions (Figure 3b). H-k analysis rendered a normal V_p/V_s ratio of 1.74 and a Moho depth of 34 km (Figure 3c). Station WP13, located at the landfall of Walvis Ridge on the remnant of the northern Etendeka basalt, has a clear Moho phase in the *S* receiver functions (Figure 3e). Although the Moho is visible by both *Pms* and *PpPms* phases in the *P* receiver functions (Figure 3d), ensuring a valid H-k analysis (Figure 3f), they are weaker and scattered due to complicated crustal structure there. An extremely high V_p/V_s ratio of 1.89 is obtained.

We performed the H-k stacking for all the stations. As multiples can be identified for most of the stations, reliable Moho depth and V_p/V_s ratio can be obtained with the H-k analysis. For five stations (WP07, WP15, WP16, WP24, and WP27), where the multiples are not clear due to either low data quality or complicated crust-mantle transition zone, a low-pass filter of 3 s is applied to ensure a reliable H-k analysis. Four of these stations are located in the north in the Walvis Ridge landfall area. The resulting Moho depth and V_p/V_s ratio maps are shown in Figure 4. The values are listed in Table S1 in the supporting information.

Figure 4a shows that the crust has a constant thickness of about 35 km in the south and becomes thicker to more than 40 km in the north of the study area. The crustal thickness is close to 35 km in the Damara Mobile Belt. There seems no apparent change in crustal thickness between the Congo Craton and the Damara Belt. The thickest crust with a thickness of up to 44 km can be found at the landfall of the Walvis Ridge close to the northern Etendeka basalts and at the border with Angola. Along the coast, the thickness is estimated to be 30 km in average with the smallest thickness of 26 km at station WP08. The V_p/V_s ratio is less than 1.75 in

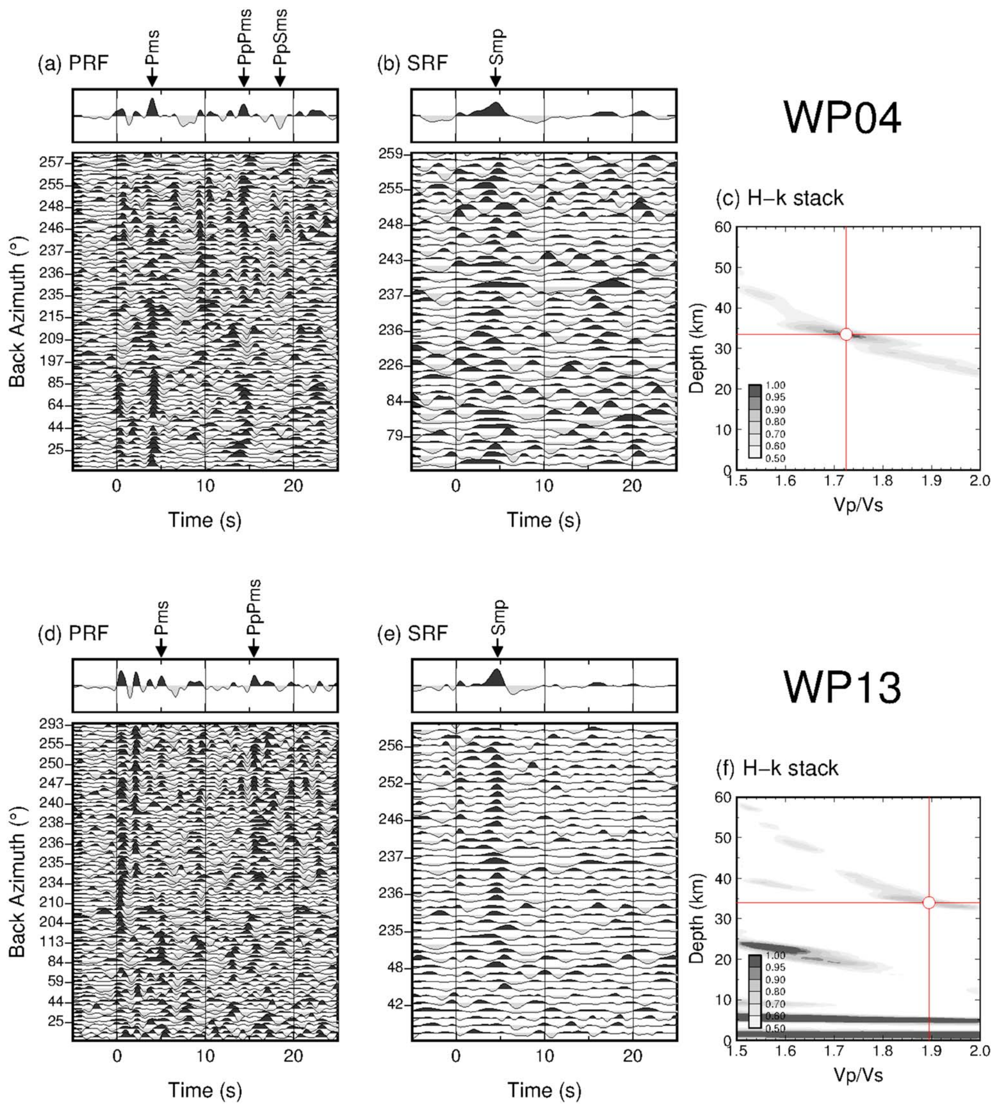

Figure 3. Examples of two stations showing individual *P* and *S* receiver functions and the H-k analysis. Station WP04, located in the Damara Belt, shows clear Moho (a) *Pms* phase and multiples *PpPms* and *PpSms* in the *P* receiver functions and (b) *Smp* in the *S* receiver functions. (c) H-k analysis gives a normal V_p/V_s ratio of 1.72 and crustal thickness of 33 km. Station WP13 is located in the landfall of Walvis Ridge. The Moho can be identified by (d) *Pms* and *PpPms* phases and (e) *Smp* phase. (f) An anomalous high V_p/V_s ratio (1.89) is obtained by the H-k analysis for a crustal thickness of 34 km.

the Damara Belt. Higher values (>1.75) can be found in the northern Etendeka plateau, extending from the coast more than 200 km toward the east, with two maximum anomalies exceeding 1.80. Extremely high V_p/V_s ratio of 1.89 is found at stations WP13 located in Kaoko Belt and WP27 near the border with Angola. The position of these high V_p/V_s ratios is concordant with the position of the impinging Walvis Ridge, where there is a considerable thickening of the crust from 30 km at the coast to 44 km toward the east beneath the Congo Craton. The uncertainties of the crustal parameters are about ±0.1 s for Moho *Ps* delay time, less than ±2 km for crustal thickness, and ±0.05 for crustal V_p/V_s ratio [see, e.g., *Geissler et al.*, 2005].

4. Discussion

The excess crustal thickness, anomalously high V_p/V_s ratio, and the complicated crustal-mantle transition beneath the continental extension of the Walvis Ridge can be interpreted as underplated layers of mafic material at the base of the crust. *Durrheim and Mooney* [1991] suggested a normal crustal thickness of

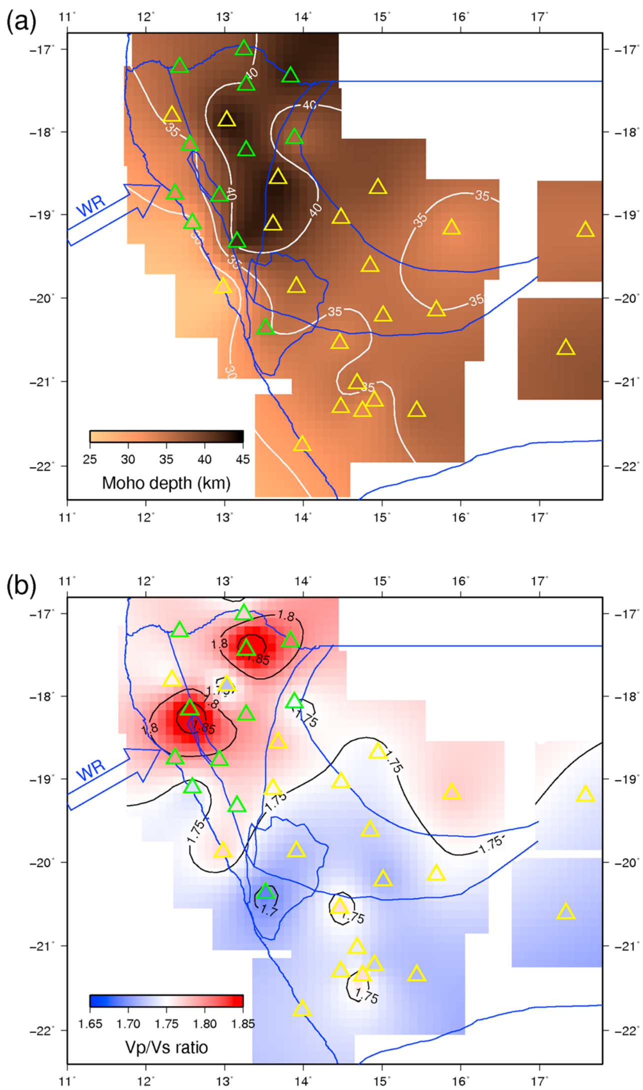

Figure 4. Maps of Moho depth and crustal V_p/V_s ratio derived by the H-k analysis. The yellow triangles denote the stations with simple Moho *Pms*. The green triangles denote the stations where the Moho *Pms* phase is either weak or characterized by complicated waveforms.

about 35 km for cratons. If we assume an age of the Congo Craton to be Archean to Paleoproterozoic [*Begg et al.*, 2009], we have an excess thickness of ~10 km beneath the Congo Craton that could be explained by magmatic underplating in agreement with observations of high V_p/V_s or Poisson's ratio. The existence of such underplated layers has been already proposed and is in agreement with similar observations in other cratonic regions in Africa and around the world as high V_p/V_s or Poisson's ratios and high V_p (~7 km/s) [e.g., *Zandt and Ammon*, 1995; *Thybo and Artemieva*, 2013; *Youssof et al.*, 2013; *Delph and Porter*, 2015].

Zandt and Ammon [1995] suggested underplating in the form of mafic basal layer as responsible for the thickening of the crust beneath cratons. Recently, *Delph and Porter* [2015] presented crustal thickness data from the nearby Zimbabwe and Kaapvaal Cratons where the Moho is observed at 35 km depth. These results are similar to our observations in the area surrounding the thickened crust as we also obtain similar depth and V_p/V_s values around 1.7. These results are therefore a strong argument in favor of our idea of magmatic underplating in the region mentioned above. In this way, we have a Craton with the original crust (35 km) and the thickened crust with mafic origin in the area of the landfall of the Walvis Rige (45 km). *Youssof et al.* [2013] suggested that some of the Archean Cratons (like Zimbabwe and Kaapvaal) in southern Africa might have suffered from piecemeal delamination processes at the base of the crust that could have removed most mafic parts of the crust and left a felsic crust with the characteristic low V_p/V_s. While considering the thickness of the crust and possible magmatic addition or basal removal, it is important to remind that the Congo Craton in the south is represented by the Angola Shield, which has been reworked during the Paleoproterozoic and is partly younger (<2000 Ma [see *McCourt et al.*, 2013]) than the Zimbabwe and Kaapvaal Cratons of Archean age (>2500 Ma) and that these cratonic units where subject of rifting, collision, and subduction before they became part of the supercontintents Rodinia (formed ~1000 Ma) and Gondwana (formed ~500 Ma) until the breakup some 180–130 Ma [see *Schneider et al.*, 2008, and references therein].

We suggest that the excess crustal thickness in our study area is the result of localized underplating in the proximity of a thermal anomaly that affected the lithosphere as suggested for Southern Africa by *Nyblade and Robinson* [1994]. The V_p/V_s ratios are low to normal in almost the entire study area (<1.75) and rather high around the impingement of the Walvis Ridge (WR) in the continent-ocean transition area (>1.8). In the same area, high V_p (>7 km/s) was observed in the lower crust by new controlled-source seismic data (Ryberg, personal communication). The high V_p/V_s ratios could be consistent with a high V_p and a normal or slightly high V_s in the region and might be reflecting the effects of the mantle thermal anomaly in form of a plume in this area in connection with mafic high-velocity material at the base of the crust. Contrary to results obtained by *Youssof et al*. [2013] and *Delph and Porter* [2015], the mobile belts in our study area (i.e., Kaoko and Damara) seem to have a thinner crust (~35 km) and normal V_p/V_s (~1.75) in comparison to the Namaqua and Limpopo Belts in the east.

The geographic position of the crustal anomalies falls within the so-called plume-related track along the Walvis Ridge, which forces us to asses if the origin is or is not plume related. If we accept the idea of magmatic underplating to explain the existence of these anomalies, then we could be observing the effects produced by the proto-TdC plume at the base of the crust during the continental breakup. Although other possibilities also remain open, as, for example, the idea that no plume is needed to produce an aseismic ridge as the Walvis Ridge [*Fairhead and Wilson*, 2005].

The presence of kimberlitic and carbonatitic pipes in this area is limited to a small region in the north [see *Moore et al*., 2008], where the presence of kimberlites is partly coinciding with the position of the northernmost high V_p/V_s anomaly displayed in our Figure 4. Kimberlites are usually limited in size (i.e., areal extension) and need material from a deeper source that could have left some remnants at the base of the crust (or underplated material) at the position of our anomalies. A kimberlite is not necessarily related to a plume nor is indicated to cause underplated mafic material at the base of the crust. In this way, it seems difficult to establish a relationship between the high-velocity underplated material with the existence of kimberlitic rocks. Furthermore, the distribution of kimberlitic magmatism is well constrained in the surrounding cratons outside the study area but remains not well constrained in the area of our array.

A crustal thickness along the coast (less than 30 km) and the Damara Belt (35 km) shows that the crust is relatively thin compared to the Brazilian coast and other mobile belts in southern Africa, respectively. Receiver functions from the Brazilian side [*Heit et al*., 2007] show a 43 km crust beneath the coast and the Parana region (the counterpart of the Etendeka), which could be indicating that the asymmetric expression of the crustal thickness on both coastal areas might have been disrupted following the opening of the Atlantic Ocean.

5. Conclusions

Receiver functions revealed a simple crustal structure with a crustal thickness of about 35 km and a V_p/V_s ratio of <1.75 in the Damara Belt. The crust is thinner in the Kaoko Belt along the coast (~30 km). A thick crust with more complicated crustal structure and a high V_p/V_s ratio is found along the extension of the Walvis Ridge toward and into the Congo Craton. We interpret the large crustal thickness and the high V_p/V_s ratio as an effect of magmatic underplating. High V_p/V_s ratios are reflecting the interaction with asthenospheric material and magmatic addition at the base of the crust of mafic composition. Areas with normal V_p/V_s ratios are more felsic and represent the craton in original state. It is possible to interpret these anomalies as induced by mantle plume interaction as responsible for this effect. One option as suggested by other authors [e.g., *Fairhead and Wilson*, 2005] is that this thermal anomaly is caused by mantle upwelling that could have caused the existence of fracture zones that propagated along the border of South America and south Africa where the cratons were affected, inducing continental breakup and magmatic addition at the base of the crust. If the plume is responsible for such a thermal anomaly, then its effects at the base of the crust are constrained to a small area and are therefore relevant only at a local scale as we are not able to see widespread changes induced by magmatic addition in the rest of the study area. In that sense, it is interesting to note that we do not observe any anomaly beneath the southern remnants of the Etendeka Flood Basalt Province and beneath the area of the intrusive centers in the SW part of the Damara Belt (Brandberg). Another option could be that the area where the anomalies are located lies at the border of the Archean Congo Craton, which has been suggested to have a thick lithosphere [e.g., *Begg et al*., 2009]. So it could be that the plume material did not reach sufficiently shallow depths under the craton to cause decompression melting, and therefore, the region of crust affected by the plume is limited.

In case that the plume is responsible for the underplated material, it is possible to suggest that it only affected a small area of less than 300 km in diameter at the base of the continental crust. In case that the plume was indeed large, then the plume material did not reach shallow depths due to the thick cratonic lithosphere.

The plume model, in which the plume is controlling plate tectonics and where the continents are rifted by plumes, should require a stronger influence of the plume on a larger scale in the lithosphere. The absence of a large-scale feature related to these anomalies might be supporting the idea that rules out the existence of a large plume head in the region during breakup.

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