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Mantle Anisotropy in NW Namibia From XKS Splitting: Effects of Asthenospheric Flow, Lithospheric Structures, and Magmatic Underplating

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Key Points:

- Upper mantle anisotropy beneath NW Namibia is a combined effect of the present-day motion of the African Plate and lithospheric structures
- No significant direct effect of the Tristan da Cunha mantle plume is observed in shear wave splitting measurements
- Localized shearing in the lithosphere and crustal underplating are likely the main causes of the lateral variations in seismic anisotropy

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

The presence of the Etendeka flood basalts in northwestern Namibia is taken as evidence for the activity of the Tristan da Cunha mantle plume during the continental breakup between Africa and South America. We investigate seismic anisotropy beneath NW Namibia by splitting analysis of core-refracted teleseismic shear waves (XKS phases) to probe mantle flow and lithospheric deformation related to the tectonic history of the region. We present the results of the joint splitting analysis of XKS data collected from 34 onshore stations and 12 ocean-bottom seismometers. The fast polarization directions (FPDs) are consistent with a model that combines the effects of lithospheric deformation and large-scale mantle flow due to the NE motion of the African plate. The dominantly NNW-SSE-oriented FPDs in the northern part are likely caused by shallow lithospheric structures. Our observations do not show any strong evidence of a pervasive effect of the Tristan da Cunha mantle plume.

Plain Language Summary

The geology of Northwest Namibia is characterized by the presence of flood basalts, originating from magma sourced in the Earth's mantle. The source magma of these flood basalts was produced during the passage of the African plate over a mantle plume, more than 80 million years ago, contemporaneous with the onset of the breakup of the South American plate from the African plate. The role of the mantle plume in the continental breakup can be examined by a seismological technique named shear wave splitting analysis. The mantle flow induces direction-dependent physical properties, that is, seismic anisotropy, which causes a shear wave to split into two different components traveling at different speeds. The leading component is polarized in a direction representing the direction of the flow in the earth's mantle. Except for the northern part, the polarization direction of the fast shear wave is consistent with the model of mantle flow caused by the NE motion of the African plate and deformations in the lithosphere. The results of our study do not show any direct evidence for the direct impact of the mantle plume on the mantle beneath our region of study.

1. Introduction

The opening of the South Atlantic oceanic basin is considered a classical example of a mantle plume-related continental breakup. The occurrence of the Paraná-Etendeka conjugate continental flood basalt (CFB) provinces (now in Uruguay and NW Namibia) is often assumed as evidence for the onset of the Gondwana breakup at ca. 130 Ma (Renne et al., 1992, 1996; Wilson, 1992). However, the role of mantle plume-plate interaction in the continental breakup and opening of the South Atlantic Ocean is still under debate. There are also several theories about the cause of the massive basaltic extrusions, including the idea of a mantle plume whose surface expression can be correlated with the present-day hotspot at Tristan da Cunha (TdC) in the South Atlantic Ocean (e.g., Fromm, Jokat, & Behrmann, 2017; Fromm, Jokat, Ryberg et al., 2017; Heine et al., 2013). The analysis of shear wave splitting to infer the pattern of mantle flow and lithospheric deformation provides a powerful tool to examine the hypothesized plume-plate interaction (e.g., Ito et al., 2014).

Our study is focused on the eastern coast of the South Atlantic Ocean and NW Namibia and includes parts of the Congo and Kalahari Proterozoic cratons as well as the Damara belt that separates the cratons and the coast-parallel Kaoko belt (Figure 1). At about 550 Ma, the Damara and Kaoko belts were developed in the Congo-Kalahari craton as evidenced by deformed Neoproterozoic rocks (Figure 2b). These belts represent the eastern arms of a triple junction within the Pan-African Orogenic System (Begg et al., 2009; Goscombe et al., 2003; Konopásek et al., 2005, Figure 1).

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The upper mantle structures beneath the study region have been explored over the last two decades by a number of seismological investigations (e.g., Celli et al., 2020; Hu et al., 2018; Moulin et al., 2010; Ryberg et al., 2015; Ussami et al., 2013; Yuan et al., 2017). Several surface-wave tomography studies have explored azimuthal anisotropy beneath the region (e.g., Hadiouche et al., 1989). Seismic tomography studies (e.g., Celli et al., 2020; De Wit et al., 2008; Hu et al., 2018; Pandey et al., 2022; Wilson, 1992) suggest that the deep lithospheric root beneath the western margins of the Congo and Kalahari cratons was eroded and delaminated by a mantle plume during the Late Cretaceous and early Cenozoic. Some other studies, including Gibson et al. (2005), support the idea that the occurrence of the CFB provinces as well as the development of Walvis Ridge (WR) is related to the activities of the Tristan da Cunha mantle plume (left inset of Figure 1). Heit et al. (2015) found a relatively thick crust (up to 45 km) at the intersection of WR and African continent. This crustal thickening was interpreted as evidence of magmatic underplating at the base of the crust induced by plume activity. Using P and S receiver function data, Yuan et al. (2017) also found that the region may have experienced underplating or plume melting, resulting in a highly melt-depleted, dehydrated boundary layer.

Long-term deformation and flow in the mantle may leave a record of seismic anisotropy in the mantle and crustal rocks (e.g., Long & Silver, 2009; Savage, 1999). The main cause of seismic anisotropy in the upper mantle is the lattice-preferred orientation of rock-forming minerals, especially olivine (Mainprice et al., 2000; Nicolas & Christensen, 1987). Seismic anisotropy can develop through large-scale mantle flow in the asthenosphere induced by present-day plate motion, underlying convection, and plume activity (e.g., Savage, 1999; Silver, 1996). Anisotropy can also be caused by lithospheric deformation formed and frozen-in during past tectonic processes (Barruol et al., 1998; Silver, 1996) beneath regions that underwent significant deformation processes (e.g., orogenic belts, extensional domains, and shear zones).

The study of seismic anisotropy, therefore, can help to address general questions relevant to the plume-lithosphere interaction and lithospheric deformation. Splitting analysis of core-refracted teleseismic shear phases (such as SKS and PKS named XKS henceforth) is a well-known approach to investigate seismic anisotropy in the mantle (e.g., Silver & Chan, 1991). As a result of the P-to-S conversion at the core-mantle boundary, XKS phases are polarized in the radial direction and lose the effects of source-side anisotropy. In a shear-wave splitting analysis two parameters, the polarization direction, φ, of the faster component of the split shear wave and the delay time, δt, between the two quasi-shear waves, are measured as proxies for the orientation and strength of seismic anisotropy beneath a seismic station.

In this study, we perform splitting analysis on XKS waveform data collected from 46 broadband seismic stations (34 land stations and 12 offshore ocean bottom stations (OBS)) to study seismic anisotropy in NW Namibia. The offshore OBS cover the eastern part of Walvis Ridge in the Atlantic Ocean. The goal of our study is to investigate the relationship between the surface structures generated by main tectonic events and internal lithospheric deformation and mantle flow. The main tectonic events to be considered include the Proterozoic continental accretion and the interaction between the Tristan da Cunha plume and the African plate and its relationship with the continental breakup and ocean rifting process since the Late Cretaceous.

2. Method and Results

2.1. Data Sets

We analyzed XKS waveform data from two temporary seismic networks XC (Kind, 2000) and 6A (Heit et al., 2010), and a permanent global station (TSUM). The network XC, consisting of 5 broadband stations with STS-2 seismometers (sensitive to the frequency range of 0.008–50 Hz) and operated from February 1998 to November 1999, was deployed to investigate the role of the mantle plume in an active continental margin. Network 6 A, deployed as part of the WALPASS (Walvis Ridge Passive Source) experiment, consists of 28 onshore broadband stations equipped with CMG-3ESP seismometers (sensitive to the frequency range of 0.003–50 Hz), in Namibia's northwestern region (operated between October 2010 and November 2012) and 12 offshore (OBS) broadband stations (operated between January 2011 and January 2012). These OBS stations were equipped with 40T seismometers which are sensitive to ground vibrations in the frequency range of 0.016–50 Hz. The network was installed to examine potential seismic anomalies related to the postulated hotspot track (Walvis Ridge) and to constrain the lithospheric and upper mantle structure beneath the passive continental margin of northern Namibia (Heit et al., 2010).

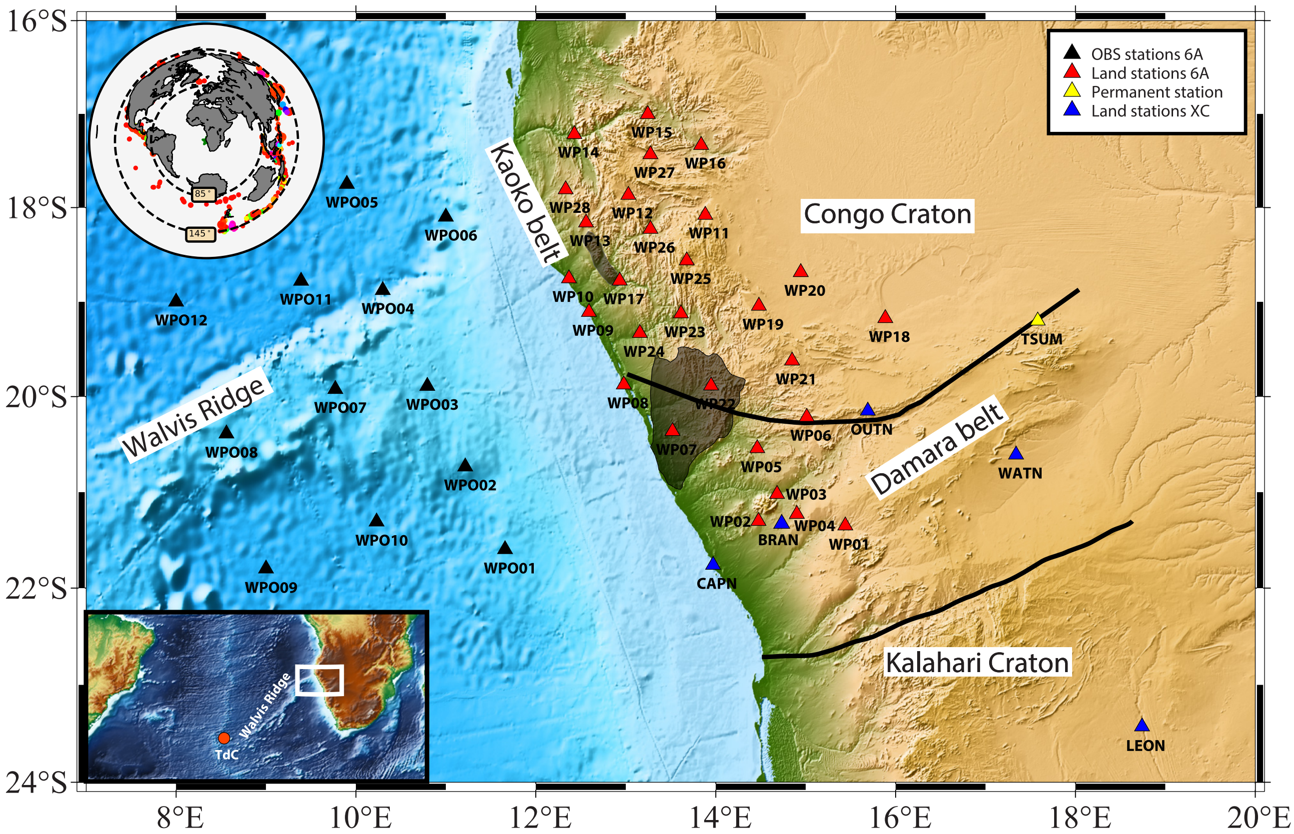

Figure 1. Map showing the study area and the location of seismic stations used in this study. Red triangles denote the network 6A (WALPASS) land stations and black triangles denote the off-shore (ocean bottom stations) stations from the same network. The blue triangles represent stations of network XC. The single permanent station in the region, TSUM, is shown by the yellow triangle. Black thick lines approximately mark the boundaries of the Congo and Kalahari cratons. Dark gray areas depict the northern and southern Etendeka flood basalts (modified after Yuan et al., 2017). The inset map at the bottom left shows the current position of the Tristan da Cunha (TdC) hotspot, and Walvis Ridge (WR). The white rectangle in the inset map denotes the study area. The global distribution of the events used in this study is shown on the map in the top left corner. The events are located within the epicentral distance range 85°–140°.

2.2. Shear-Wave Splitting Analysis

XKS waveform data were collected from teleseismic events in the epicentral distance range 85°–140° (Figure 1) and with magnitudes Mw > 6.0, which provided a total number of ~2450 seismograms from 457 events. The splitting analysis was performed using the SplitRacer code (Reiss & Rümpker, 2017). The origin time and location of the teleseismic events were taken from the National Earthquake Information Center (NEIC). The theoretical arrival times of XKS phases are calculated based on the IASP91 reference model to determine the time window for splitting analysis. Seismograms are generally filtered between 0.02 and 0.2 Hz in order to eliminate long-period and high-frequency noise that might interfere with the XKS waveform. Three steps are involved in pre-processing of the waveform data set: (a) initial screening where the filtered XKS waveforms are selected based on their signal-to-noise ratio, (b) visual quality check: only phases that meet the previous criteria are displayed and by visual inspection, only phases suitable for splitting analysis are kept (based on the sharpness of the waveform and the shape of the particle motion), (c) we check for possible misalignment of the sensors based on the difference between the theoretical back-azimuth and the azimuth of the principle axis of the long-period elliptical particle motion (see also Rümpker & Silver, 1998). In the case of misalignment of a sensor, the horizontal seismograms are rotated to the correct azimuth before splitting analysis. For the OBS stations, since no information about the seismometer orientation was available, the estimated misalignments are used to rotate the horizontal seismograms to NS and EW components. We also have the option to manually choose a time window over which the XKS phase is captured correctly with less interference from other phases. There are some factors such as the aspect ratio of the elliptical particle motion to help us with selection.

Following the first step of pre-processing, selection and orientation correction, single measurements are computed from individual XKS phases based on the transverse-component energy-minimization approach (Silver

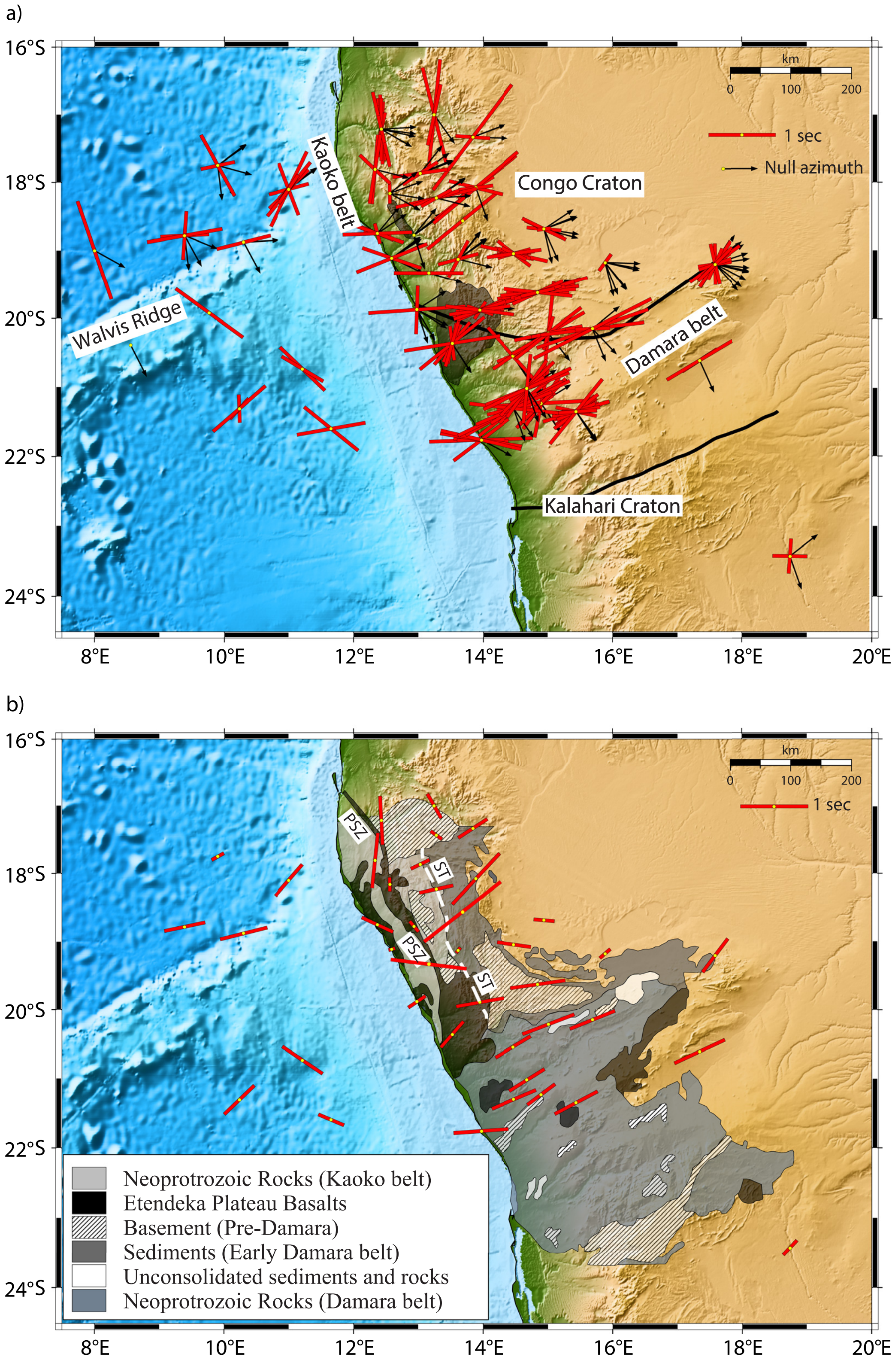
a)
16°S
18°S
20°S
22°S
24°S
8°E
10°E
12°E
14°E
16°E
18°E
20°E
km
0
100
200
1 sec
Null azimuth
Congo Craton
Kaoko belt
Walvis Ridge
Damara belt
Kalahari Craton
b)
PSZ
ST
Neoprotrozoic Rocks (Kaoko belt)
Etendeka Plateau Basalts
Basement (Pre-Damara)
Sediments (Early Damara belt)
Unconsolidated sediments and rocks
Neoprotrozoic Rocks (Damara belt)

Figure 2.

& Chan, 1991). For a selected time window, the splitting parameters φ and δt are determined so that energy on the transverse component of the seismogram is most effectively reduced. The main goal of the single-phase analysis is to verify the suitability of each phase for the final joint inversion of multiple phases observed at a single station. Furthermore, the azimuthal variations of the single measurements at each station provide a first indication of the complexity of the anisotropic structure beneath the station. The single measurements are considered reliable if the horizontal fast-and slow-component waveforms are coherent, and the initial particle motion is elliptical and becomes linear after correction for anisotropy (Silver & Chan. 1991). The SplitRacer code allows for selecting an initial time window encompassing the phase under analysis. It then automatically chooses a number of alternative time windows (up to 10 windows here), with start and end values randomly distributed around corresponding values for the initial window. Splitting analysis is then performed for all the selected time windows and the mean value of the splitting parameters is reported as the single measurement for the selected phase. SplitRacer also enables categorizing the single splitting measurements by assigning quality such as good, average, and poor to each measurement. This is done manually based on the elliptical shape of the particle motion, the percentage of reduction in energy on the transverse component, the size and form of the 95% confidence contour, the distribution of φ and δt values from different chosen time windows, and the correlation between fast and slow split shear waves components. All single measurements are presented via a spreadsheet (Table S1) in Supporting Information S1. Two examples of the categorized measurements are shown in Figure S1 in Supporting Information S1. Some measurements are also categorized as "null" based on the linearity of the uncorrected particle motion and reduction of T-component energy. A null measurement is obtained from a non-split waveform when either there is no anisotropy beneath the station, or the initial polarization direction of the wave is parallel to either the fast or slow axis in the anisotropic layer.

Finally, phases corresponding to good and average single measurements are selected for the joint splitting analysis at each station. The joint splitting analysis inverts all qualified waveforms at a given station, including those phases giving good and fair null measurements. In this approach, a grid search is applied to find two splitting parameters (φ and δt, equivalent to the anisotropic parameters of a 1-layer model) which simultaneously minimize the total energy of all T-component waveforms at the station. The correction of the T-component waveforms for anisotropy is performed using an inverse splitting operator (Rümpker & Silver, 1998).

2.3. Results

The results of the single-phase splitting measurements (Table S1 in Supporting Information S1) are shown on the map at station locations in Figure 2a. Red bars in this figure indicate fast polarization directions (FPDs) with lengths proportional to the associated delay times. The black arrows show back-azimuths of events giving null measurements. We obtained considerable reliable measurements at land stations, though the offshore stations give relatively fewer measurements. The single measurements at the majority of the land stations show fast-polarization directions dominantly oriented in a NE-SW direction in the south and NNW-SSE direction in the north. We also obtained null measurements (black arrows in Figure 2a) with back-azimuths mainly either parallel or perpendicular to the fast directions. These observations generally suggest that the anisotropic structure can vary laterally beneath the region, though in each subregion one process has the dominant effect on shear waves. Furthermore, we observe azimuthally varying measurements at a few stations. For example, at station TSUM with more than two decades of data, we obtained relatively small delay times and many null measurements, suggesting local structural complexity beneath the station.

Variations of splitting parameters (φ and δt) with respect to back-azimuth and incidence angle may indicate layered anisotropy or more complex structures (e.g., Hartog & Schwartz, 2000; Rümpker & Silver, 1998; Silver & Savage, 1994). In the case of depth-dependent anisotropy, φ and δt are expected to exhibit a $\pi/2$ periodicity as a function of back-azimuth. Examples of the variation of the single splitting parameters as a function of the event back-azimuths are shown in Figure S2 in Supporting Information S1, at stations with more than 10 reliable measurements. We tried to invert the splitting parameters for 2-layer anisotropic models at stations with sufficient

Figure 2. (a) Map showing splitting parameters of single XKS waveforms. The non-null splitting parameters are shown with red bars oriented in the fast direction with length proportional to the delay time. The thin black arrows indicate the back-azimuth of phases giving null splitting measurements. (b) 1-layer parameters obtained from joint-splitting analysis of XKS waveforms for each station. The red bars are oriented in the fast polarization direction with length proportional to the delay time. The main geological units in northwestern Namibia (after Konopásek et al., 2005) are also schematically depicted on the topography map. PSZ: Puros Shear Zone; ST: Sesfontein Thrust.

back-azimuthal coverage. Examples of the 2-layer modeling for stations WP01 and TSUM are shown in Figures S3c and S3d in Supporting Information S1. Our analysis suggests that the 2-layer models cannot explain the data better than the 1-layer models (Figures S3a and S3b in Supporting Information S1). Similar results are obtained for other stations suggesting that the assumption of a 1-layer anisotropic model beneath most of the study area is valid within the range of the azimuthal coverage of our data set. We argue that the variation of splitting parameters at stations such as TSUM can be due to local 3-D heterogeneities (e.g., Salimbeni et al., 2007; Vauchez et al., 2000) rather than a simple 2-layer model with horizontal symmetry axes.

Following the analysis of the single measurements, we conclude that the assumption of 1-layer anisotropy beneath the stations is valid within the range of our observations. Therefore, we jointly analyze the XKS phases of each station to obtain effective splitting parameters representative of the 1-layer models. The 1-layer model parameters for all stations obtained by the joint analysis are shown in Figure 2b and Table S2. Table S2 also shows that the amount of useful phases varies for each station. No reliable joint analysis could be performed at 5 OBS stations (WPO 03, 07, 08, 09, and 12) and from the land station BRAN (Figure 1) due to the relatively low signal-to-noise ratio of the XKS waveforms. We observe a consistent NE-SW trend of the single-layer fast directions at the majority of the stations. On the other hand, we see an anticlockwise rotation of the fast directions from the dominantly NE-SW direction in the SW region to an NNW-SSE direction in the NW region of the study area. The possible scenarios for the cause of seismic anisotropy and its lateral variation beneath the region are discussed in the next section.

3. Discussion

One objective of this study is to examine the plume-plate interaction in a region where the emplacement of extensive CFB is thought to mark the onset of the opening of the South Atlantic Ocean in the Cretaceous. The track of the potential mantle plume can be traced from NW Namibia over Walvis Ridge to the present-day hotspot at Tristan da Cunha (TdC) (Richards et al., 1989). The results of the XKS splitting analysis presented in this study show a relatively uniform pattern with local small-scale variations in the splitting parameters. We discuss these results in a broader context of the African plate motion and possible scenarios regarding how the mantle plume and local structures could have left signatures in terms of seismic anisotropy.

3.1. Plate-Motion-Induced Mantle Flow

In order to consider the XKS splitting pattern in a broader context in western Africa, we show in Figure 3 our results (red bars) alongside measurements (blue bars) from previous studies (see Barruol et al., 2009). The fast polarizations generally trend NE-SW, in agreement with previous studies. Also, our measurements of joint splitting parameters at station TSUM agree well with previously reported results (Barruol & Ismail, 2001), with minor differences in φ (6°) and δt (0.2 s).

The relatively coherent and predominantly NE-SW-oriented pattern of the observed FPD in western Africa is subparallel to the present-day plate motion indicated by the black arrows in Figure 3 in the No-Net-Rotation reference frame (Kreemer et al., 2014). These observations suggest that the large-scale mantle flow due to the motion of the African plate relative to the underlying asthenosphere plays a major role in the development of the observed anisotropy. This uniform pattern of anisotropy is locally perturbed, which could be an effect of the lithospheric structure.

3.2. Large Scale Mantle-Plume Signature?

Previous studies suggest that a mantle plume was active beneath the region during the continental breakup, likely emplaced before the onset of the breakup (e.g., Brune et al., 2013; Brune et al., 2016; Heine et al., 2013). This mantle plume could have left signatures in the pattern of mantle flow beneath NW Namibia. However, the lateral extent of the affected area by the mantle plume is not clearly known. Fromm et al. (2015), Fromm, Jokat, and Behrmann (2017), using seismic refraction data, identified structures suggesting that no broad plume head existed during the opening of the South Atlantic that modified the continental crust on a large scale. They also suggest that anomalous mantle melting may have occurred only locally.

The complex pattern of seismic anisotropy in active hot spot regions described in previous investigations (e.g., Barruol & Fontaine, 2013; Collins et al., 2012; Ito et al., 2015; Waite et al., 2005; Walker et al., 2005) reflects

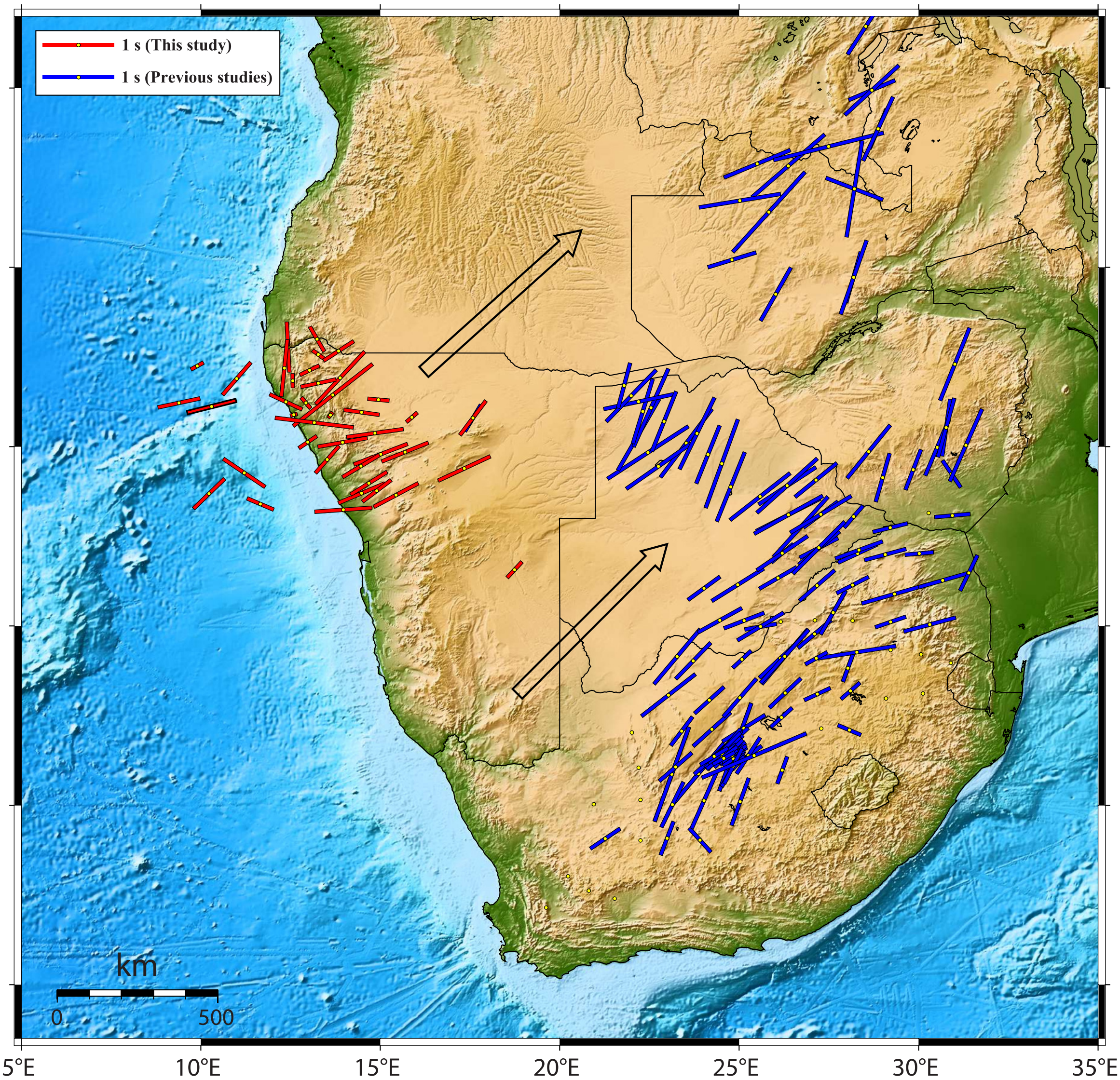

Figure 3. Map showing the joint splitting parameters of this study (red bars), and the mean splitting parameters from the previous studies in Africa (blue bars; see Barruol et al., 2009). The bars are oriented in the fast polarization direction with length proportional to the delay time. The two plain arrows indicate the absolute motion vector of the African Plate in a No-Net-Rotation reference frame (Kreemer et al., 2014).

the signature of mantle plumes. An active rising mantle plume can produce a radial asthenospheric flow beneath a lithospheric plate when the plate is steady relative to the plume head. This radial flow is, however, converted to a parabolic flow when the plate moves relative to the underlying plume (e.g., Druken et al., 2013; Ito et al., 2014; Walker et al., 2001). The XKS splitting measurements in our study do not exhibit such radial or parabolic patterns. The movement of the lithospheric plate during the last ∼130 Ma could have erased the original effects of the mantle plume. Furthermore, the possible plume-induced fabric was likely reworked by later phases of continental breakup, lithospheric erosion, and subsequent lithospheric thickening. Seismic tomography models (e.g., Celli et al., 2020; Hu et al., 2018; Pandey et al., 2022) suggest that the lower part of the lithosphere was eroded and delaminated by the mantle plume in the early Cretaceous. The thickness of the lithosphere was later resumed by cooling of the plume melts and accretion of the depleted lithospheric segments. These lithospheric removal and reconstruction processes could have erased the potential fabric originally generated by the mantle plume.

The effect of the mantle plume could also be observed along Walvis Ridge (WR) as the existing track of the mantle plume. It is possible that several layers of anisotropy exist in mantle beneath WR. The upper anisotropic layer might be due to early structures acquired at the ridge, whereas the lower anisotropic layer could result from plume-induced deformation and absolute plate motion (APM). The limited availability of reliable OBS data in this area, however, makes it difficult to confirm the source of anisotropy.

3.3. Effects of the Neoproterozoic Lithospheric Structures

The splitting parameters of the 1-layer anisotropic model beneath each station are depicted in Figure 2b together with the main geological units including the Kaoko and Damara belts, the Puros shear zone, and the Kalahari and Congo cratons.

As discussed in Section 3.1, the dominantly NE-SW trend of the observed FPDs in the central parts of the study area including the Damara belt is consistent with the large-scale regional trend of anisotropy in western Africa parallel to the APM. However, this trend is also subparallel to the surface structures in the Damara belt (Figure 2b). This suggests that the observed FPDs can also be due to the frozen-in lithospheric anisotropy generated during the Neoproterozoic (Pan-African) orogeny during the amalgamation of western Gondwana, as was also suggested by Barruol and Ismail (2001) for station TSUM. However, the parallel directions of the potential frozen lithospheric anisotropy and the present-day large-scale mantle flow bring an ambiguity about the relative contribution of the sources of anisotropy.

In the north, we observe a dominantly NNW-SSE trend of FPD at the majority of the stations located in the Kaoko belt, exhibiting an anticlockwise rotation relative to the general NE-SW trend of the FPDs in western Africa. Considering this small-scale variation in the FPDs and the fact that the effective values of δt (from the joint splitting analysis) for all the stations are below one second, we conclude that this pattern in splitting parameters is related to lithospheric anisotropy sources. By considering the variations of FPDs at neighboring stations (WP12 and WP27) and computing the Fresnel-zone widths (Rümpker & Ryberg, 2000), we estimate that the lateral change in the anisotropic structure occurs at depths between 30 and 60 km, corresponding to 35% and 45% of overlap of the Fresnel zones at nearby stations. We, therefore, attribute the NNW-SSE trending seismic anisotropy in NW Namibia to the effect of the tectonic evolution of the lithosphere, including the formation and evolution of the Kaoko orogenic belt.

There are two major structural units in the Kaoko belt: the Puros Shear Zone and the Sesfontein Thrust (Figure 2b), which divide the belt into three different tectonic units (Konopásek et al., 2005). The Kaoko belt has evolved in different phases. Following an early thermal phase that resulted in pervasive partial melting and granite emplacement in the western zone (656 Ma), a transpressional phase shaped the geometry of the belt (580–550 Ma). Strain partitioning in the Puros shear zone and the NE-SW oriented shortening in the Central zone supports a sinistral transpressional movement in the second phase, followed by a minor NNW-SSE shortening (530–510 Ma). Due to the extensive and large-scale nature of these Precambrian tectonic processes, which could also have affected the upper mantle beneath the Kaoko belt, they could have produced a pervasive NNW-SSE oriented anisotropic fabric sub-parallel to the strike of the Puros shear zone.

The Ribeira belt (the Brazilian counterpart of the Kaoko belt) formed the western arm of the triple junction within the Pan-African orogenic system (Begg et al., 2009; Coward, 1981). The shear wave splitting analysis by Heintz et al. (2003) revealed that anisotropy beneath the Ribeira belt is subparallel to the regional shear zones. The presence of the lithospheric anisotropy subparallel to the rift margins along the Kaoko and Ribeira belts provides a support for the notion that the late Mesozoic lithospheric rifting in Africa has started along the pre-existing Proterozoic lithospheric structures, as also suggested by Vauchez et al. (1997, 1998).

3.4. Magmatic Underplating During Continental Breakup

Magma intrusion in rift zones is a mechanism that can induce shape-preferred orientation fabrics in the form of melt pockets and vertical dike structures (e.g., Hammond et al., 2014). Magmatic underplating during the Cretaceous continental rifting in western Africa could have produced seismic anisotropy in the lower crust by the intrusion of magma organized in dike structures subparallel to the rift margin and also by heating the pre-existing lower crust, thus promoting plastic flow and enabling alignment of anisotropic minerals, a mechanism that was also observed in other tectonic settings (e.g., Clement et al., 1994; Wu et al., 2022).

Ryberg et al. (2015) identified a narrow region of high seismic velocity anomalies in the middle-lower crust beneath northern Namibian and interpreted them as a mafic intrusion into the crust. A study by Planert et al. (2017)

argues that rift-related lithospheric stretching and associated transform faulting can play a major role in locating magmatism. Coast-parallel faults that likely penetrate down to the base of the lower crust (Foster et al., 2009; Fromm et al., 2015) also indicate a zone of stretching that could have facilitated magmatic intrusion beneath the crust. We argue that the NNW-SSE-oriented FPDs observed in NW Namibia is partially affected by the seismic anisotropic fabric developed in the lower crust by magmatic underplating. One should also consider that a lower layer of anisotropy can likely exist beneath this region with a NE-SW trend of fast polarization generated by horizontal shearing due to plate motion. However, our observations are mainly affected by an NNW-SSE-oriented anisotropy and the limited azimuthal coverage does not allow examining the presence of two layers of anisotropy.

4. Conclusion

We present new results of the upper mantle seismic anisotropy beneath NW Namibia. From XKS splitting analysis, we detect seismic anisotropy at the majority of the 45 land- and OBS stations used in this study. Our measurements suggest that the upper mantle anisotropy in the study area is due to a combined effect of large-scale mantle flow related to the absolute motion of the African plate (APM) and lithospheric structures developed during the Neoproterozoic orogeny. The parallelism between the structural trends in the Damara belt and the APM direction makes it ambiguous to determine the relative contribution of the lithospheric and asthenospheric sources of anisotropy. To the north beneath the Kaoko belt, where the NNW-SSE trend of the FPDs is mainly subparallel to the Neoproterozoic shear zone and rift margin, the main source of anisotropy likely resides in the lithosphere. The lithospheric anisotropy beneath the Kaoko belt was developed by the superposition effect of two main tectonic processes. One is the underplating and emplacement of melt pockets within cracks in the uppermost mantle and at the base of the crust. The other process is the shearing in the Puros shear zone, which affected the entire thickness of the lithosphere. We also conclude that it is not possible to clearly decipher a mantle-flow signature of the Tristan da Cunha mantle plume beneath western Africa. The potential mantle plume effect was likely overprinted by subsequent plate motion, continental breakup, and processes during the Cenozoic that have led to the resumption of the thickness of the lithosphere.

Data Availability Statement

Data: Data from the networks XC and 6A are accessible from GEOFON/GFZ via the following links: XC: https://doi.org/10.14470/KP6443475642. 6A: https://doi.org/10.14470/1N134371. Station TSUM belongs to the Global Seismograph Network (code IU, doi: https://doi.org/10.7914/SN/IU). XKS splitting waveform data are taken from SKS-Splitting-database. Université de Montpellier, Laboratoire Géosciences (https://doi.org/10.18715/SKS_SPLITTING_DATABASE). The information about the origin time and location of the teleseismic events were taken from the National Earthquake Information Center (NEIC) these are available on the U.S. Geological Survey (USGS) website at http://earthquake.usgs.gov. *Software*: The data analysis was performed using the MATLAB code SplitRacer. The code is available via the link: https://www.geophysik.uni-frankfurt.de/64002762/Software. *Graphs*: The figures presented in the paper were generated using the analysis code (SplitRacer) and PyGMT (https://www.pygmt.org).

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