

Upper mantle anisotropy of the Borborema Province, NE Brazil: Implications for intra-plate deformation and sub-cratonic asthenospheric flow

Ian D. Bastow^{1*}, J. Julià², A.F. do Nascimento², R.A. Fuck³, T. Buckthorp¹, J. McClellan¹

(4th June 2015)

¹ Department of Earth Science and Engineering, Imperial College London, London, SW7 2AZ, UK.

² Departamento de Geofísica & Programa de Pós-Graduação em Geodinâmica e Geofísica, Universidade Federal do Rio Grando do Norte, Natal, 59072-970, Brazil.

³ Instituto de Geociências, Universidade de Brasília, Brasília, Brazil.

* Corresponding author: e-mail: i.bastow@imperial.ac.uk

Abstract

The geological record of the Borborema Province, northeast Brazil, documents tectonic events that characterised the Precambrian formation and Mesozoic breakup of Gondwana. Large-scale shear zones and associated granitic plutons that developed during the Neoproterozoic Brasiliano/Pan-African orogeny, and major sedimentary basins of Mesozoic age, indicate significant deformation across the region. However, whether or not the shear zones resulted from Precambrian terrane accretion, or are simply the result of episodes of subsequent intra-plate deformation is debated. Also poorly understood is the effect of the thick São Francisco mantle keel on present-day asthenospheric flow. To address these issues we have performed a teleseismic shear wave splitting study of mantle seismic anisotropy from a new broadband seismograph network centred on the Borborema Province. Shear wave splitting parameters (ϕ , δt) reveal a lack of plate-scale anisotropic fabrics associated within the continental interior, perhaps supporting models of formation and evolution of the Borborema Province involving minimal deformation of the lithospheric mantle. Delamination of anisotropic lithosphere during the development of Cenozoic volcanism that eroded older fossil lithospheric fabrics is unlikely because the widespread Cenozoic magmatism required to achieve this is absent in the geological record. Instead, the apparently low levels of seismic anisotropy observed in the interior of the Borborema Province may simply reflect depth-dependent anisotropy: nulls/low δt observations may be the subtractive result of orthogonal fast directions in the lithosphere and asthenosphere. Towards the Brazilian coast $\delta t > 1$ s, and fast directions are sub-parallel to stretching fabrics formed during the

opening of the South Atlantic. This may imply that the mantle lithosphere was deformed but not completely destroyed during Gondwana breakup. However, a more complete backazimuthal coverage of splitting measurements across the region is needed to confirm or refute these hypotheses unambiguously.

Key words: Brazil, Gondwana, Keel, Lithosphere, Anisotropy.

1 Introduction

Regions of Precambrian geology (shields) are generally considered to be underlain by stable portions of Earth's continental lithosphere, which have survived thermal and mechanical erosion for up to billions of years. However, the extent to which they are internally deformed during multiple Wilson cycles is debated (e.g., Sleep, 2003). Major shear zones scar the interiors of some continental masses, hundreds of kilometres from plate boundaries, but the extent to which they deform the lithospheric mantle is uncertain (e.g., Vauchez et al., 2012). The lithosphere beneath shields can also have a major impact on present-day asthenospheric flow: lithospheric roots, or keels, can extend to 250km and more into the mantle (e.g., Polet and Anderson, 1995; Artemieva and Mooney, 2001), and may affect present-day mantle flow, either by deflection of the ambient mantle flow field, or by the stimulation of small-scale convection cells at their flanks (King and Anderson, 1998; Fouch et al., 2000; King and Ritsema, 2000; Sleep et al., 2002). The geological record of northeast Brazil (Figure 1) documents tectonic events that span almost three quarters of Earth history, from Archean formation of the São Francisco craton and portions of the Borborema Province, through the Neoproterozoic Brasiliano/Pan-African orogenies, and to the Mesozoic formation of the equatorial South Atlantic (e.g., Goodwin, 1996; Brito-Neves and Cordani, 1991; Cordani et al., 2003). The region is thus an ideal natural laboratory for the study of multi-phase lithospheric deformation, and present-day mantle flow influenced by a cratonic root.

Large-scale shear zones and associated granitic plutons developed in the Borborema Province of northeast Brazil (Figure 1) during the Neoproterozoic Brasiliano/PanAfrican orogeny, with large-scale dextral, strike-slip faults cross-cutting Archean basement, Paleoproterozoic-to-Mesoproterozoic supracrustal and crystalline rocks, and Neoproterozoic granites (e.g., Vauchez et al., 1995; Ganade de Araujo et al., 2014). Younger, Phanerozoic deformational events, including marginal and intra-plate sedimentary basin development during the opening of the South Atlantic, imply considerable tectonic reworking of the continental interior since the formation of Gondwana (de Matos, 1992). On the other hand, some workers (e.g., Neves, 2003; Neves et al., 2006, 2008) have proposed the Borborema Province has behaved as a single tectonic unit since ~2.0Ga. Neves et al. (2008), for example, argue that lateral variations in the concentration of heat-producing elements in the lithospheric mantle can lead to

73 significant, localised plate heating and weakening, which subsequently promotes strain
74 localisation in an intraplate setting. Thus, whether or not the large-scale shear zones in
75 the region are the result of Precambrian terrane accretion, or are simply the plate-scale
76 remnants of episodes of Precambrian intra-plate deformation, remains enigmatic.
77 Questions also remain concerning present-day mantle flow beneath the Borborema
78 Province. Knesel et al. (2011) and de Oliveira and Medeiros (2012), for example, have
79 suggested that small-scale convection at the northern flank of the São Francisco craton is
80 responsible for coeval Cenozoic volcanism and uplift in the Borborema region, but the
81 geophysical constraints on mantle flow required to confirm or refute this hypothesis are
82 presently lacking.

83
84 When a shear wave encounters an anisotropic medium, it will split into two orthogonal
85 shear waves, one traveling faster than the other (e.g., Silver, 1996). The polarisation of
86 the fast component (ϕ), and the time delay (δt) between the fast and the slow shear wave
87 provide simple measurements that characterise seismic anisotropy. Phases involving P-to-
88 S conversions at the core-mantle boundary, such as SKS, PKS, and SKKS, are ideally
89 suited for shear-wave splitting studies of the upper mantle directly beneath a seismograph
90 station because they are radially polarised at the core-mantle boundary and thus record no
91 source-side anisotropy (e.g., Savage, 1999; Long and Silver, 2009). Olivine is the most
92 abundant mineral in Earth's upper-mantle and is highly anisotropic. Strain can lead to the
93 development of crystallographic preferred orientation (CPO) of olivine, with alignment
94 of its a-axes in the flow direction (e.g., Zhang and Karato, 1995; Bystricky et al., 2000;
95 Tommasi et al., 2000), assuming steady-state, one dimensional shear flow (Kaminski and
96 Ribe, 2002). Shear wave splitting parameters can thus be related, for example, to
97 asthenospheric flow (e.g., Vinnik et al., 1989, 1992; Fouch et al., 2000; Sleep et al.,
98 2002), the preferential alignment of fluid or melt (e.g., Blackman and Kendall, 1997),
99 pre-existing anisotropy frozen in the lithosphere (e.g., Silver and Chan, 1988; Vauchez
100 and Nicolas, 1991; Bastow et al., 2007), or any combination thereof.

101
102 In this study, we present a teleseismic shear wave splitting study of crust and mantle
103 anisotropy in NE Brazil using data recorded by a new seismograph network comprising
104 22 broadband stations (Figure 1). These instruments extend from the Archean São
105 Francisco craton in the south, to the equatorial margin in the north. Ours is the first
106 regional study of mantle anisotropy beneath NE Brazil using teleseismic shear wave
107 splitting, though neighbouring studies do exist: to the south of our study area, in SE
108 Brazil, Heintz et al. (2003) and Assumpção et al. (2006) observed large splitting delay
109 times (>2.5 s), which they cited as evidence for co-aligned fossil lithospheric fabrics and
110 sub-lithospheric mantle flow: the two anisotropic layers are postulated to interfere
111 constructively, yielding the large delay times. Assumpção et al. (2011) carried out a
112 splitting study of the entire South American stable platform, but that study featured only

two stations in the Borborema Province. Studies of local earthquakes in the Borborema Province indicate that the crust records fossil anisotropic fabrics that parallel regional metamorphic trends (e.g., do Nascimento et al., 2002, 2004), but splitting delay times for these shallow (≤ 5 km) events vary considerably between 1 and 28ms per kilometre of crust sampled. Our study of SKS splitting in the region thus has important implications for our improved understanding of the tectonic development of the NE Brazilian lithosphere, as well as the present-day mantle flow-field beneath it.

2 Geology and tectonic framework

The Borborema Province of NE Brazil is located in the northeasternmost corner of the Brazilian shield (Figure 1). It is bound to the south by the São Francisco craton, to the west by the cratonic Parnaíba basin, and to the north and east by a number of marginal basins that developed during the opening of the Atlantic. The basement of the Borborema Province comprises rocks of Paleoproterozoic age and small Archean nuclei. Supracrustal formations include metamorphic rocks with ages ranging from Paleoproterozoic to Neoproterozoic (e.g., Vauchez et al., 1995; Neves, 2003; Van Schmus et al., 2008).

The Borborema Province is thought to have formed during the Neoproterozoic Brasiliano/Pan-African orogeny, which culminated in the formation of the Gondwana supercontinent. In the accretionary model, the province is considered to have formed by the amalgamation of small continental fragments and plates that existed between the West African–São Luiz craton to the north and the Congo–São Francisco craton in the south (Jardim de Sá et al., 1992; Cordani et al., 2003). The Brasiliano orogeny resulted in the development of numerous shear zones, several hundreds of kilometres long and tens of kilometres wide, which collectively form a mechanically coherent array over more than 200,000km² (e.g., Vauchez and da Silva, 1992). The shear zone developed concomitant with high-temperature, medium-to-low pressure metamorphism and magmatism involving both crustal and mantle-derived melt sources and can be split broadly into two domains: a western zone of NE-striking strike-slip faults (e.g., the Sobral shear zone and the Senador Pompeu shear zone: Figure 1), and eastern zone of more sinuous, discontinuous shear zones (see e.g., Vauchez et al., 1995, for a more comprehensive review). Some of the Borborema shear zones can be continued into the African continent in paleogeographic reconstructions: the Central African Shear Zone (Trompette and Carozzi, 1994; Van Schmus et al., 2008; Santos et al., 2008; Arthaud et al., 2008; de Oliveira et al., 2010).

Refinements to the accretionary model for the formation of the Borborema Province have been proposed based on radiometric dating of rocks and/or interpretation of gravimetric and magnetic surveys, which introduced smaller tectonic-stratigraphic terrains and

multiple orogenic cycles into the amalgamation process (e.g., Van Schmus et al., 2011). Other authors, nonetheless, have argued that the Borborema Province was instead part of a large tectonic block that has behaved as a single unit since 2.0Ga, with Brasiliano deformation in the region occurring in an intra-continental, not plate boundary setting (e.g., Neves, 2003; Neves et al., 2006). Vauchez et al., (1995) consider that shear zones in the Borborema province record intra plate deformation; others (e.g., Tommasi et al. 1995; Tommasi and Vauchez, 1997) have modeled the system as one of intraplate strain localisation in response to pre-existing, lateral variations in thermal-rheological plate structure. In these models, microplate amalgamation largely predates the Pan-African orogeny, which, in the Borborema province, only partially reworked preexisting plate structures. Given the geometry of the shear zones, Tommasi et al. (1995; 1997) concluded that the thick E-W shear zones of the Borborema province only accommodated low strains; they acted instead as strain transfer zones at the tip of the São Francisco craton. The Borborema Province shear zones may therefore not have modified Archean and Proterozoic mantle fabric considerably.

The Mesozoic evolution of the Borborema Province was marked by the opening of the south Atlantic, which separated the province from its African conjugate (e.g., de Matos, 1992; Cordani et al., 2000). Significant crustal thinning affected the region during continental rifting (e.g., de Castro et al., 1998; Lima et al., 2015), which formed both marginal (e.g., Ceará, Potiguar, Pernambuco-Paraíba, Sergipe-Alagoas: Figure 1) and intra-continental (e.g., Araripe, Rio do Peixe, Iguatu, Tucano: Figure 1) sedimentary basins.

The post Gondwana breakup evolution of the Borborema Province is characterised by recurrent magmatism and episodes of uplift of the Borborema plateau. Mesozoic-Cenozoic magmatism in the province is small-volume, long-lived, alkaline, and arranged along two mutually perpendicular magmatic lineaments overlapping in time for at least 5Ma (Knesel et al., 2011). The offshore E–W trending Fernando de Noronha-Mecejana Volcanic lineament (FNMA) has K-Ar and $^{40}\text{Ar}/^{39}\text{Ar}$ dates ranging from ca. 34-2 Ma (Mizusaki et al., 2002), while the on-shore N-S trending Macau-Queimadas volcanic lineament (MQA) has ages in the 93-6.4Ma range (Mizusaki et al., 2002; Knesel et al., 2011) and no clear age progression. Cenozoic uplift of up to ~1200m was inferred from relative dating of the elevated sediments of the Serra dos Martins formation in the northern Borborema Plateau, in the eastern half of the province (Moraes Neto et al., 2009; de Oliveira and Medeiros, 2012), although absolute dating from apatite fission-track analysis of granitic-gneissic samples suggest a Late Cretaceous initiation for the uplift (Moraes Neto et al., 2009). The Cenozoic volcanism in the Borborema province has been attributed to an active, small-scale convection cell under the continental edge (e.g., Knesel et al., 2011), which might have also been responsible for mafic underplating of

the Borborema Plateau and isostatic uplift coeval with surface volcanism (de Oliveira and Medeiros, 2012).

Although a thin layer of mafic underplate south of the Patos Lineament seems to be consistent with receiver function observations, the time of emplacement of such a layer of mafic cumulates is debated (Luz et al., 2015a; 2015b). In particular, Luz et al. (2015b) argue that the southern Borborema plateau is a high-standing, rheologically strong block that resisted deformation during Brasiliano compression and Mesozoic extension. The mafic layer would be of Proterozoic origin and it would have delaminated from the surrounding Borborema crust during the Brasiliano orogeny. The delaminated crust would then have been stretched and thinned during the Mesozoic to form the low-lying regions that surround the southern plateau. During the extension process, an intracrustal detachment zone, perhaps linking the extensive network of shear zones at depth, would have formed in the regions of thin crust (Almeida et al., 2015). Part of the thinned crust would have experienced uplift during the Cenozoic and formed the northern Plateau.

3 Data selection and shear wave splitting analysis

Broadband teleseismic data for this study come from past and present seismic networks operating in the Borborema Province and adjacent regions (Figure 1). The bulk of the dataset was recorded by the 15 seismograph stations of the Rede Sismográfica do Nordeste (RSISNE) monitoring network. RSISNE stations, which became fully operational in mid 2011, are equipped with RefTek 151-120A broadband sensors with flat response in velocity for periods between 120s and 50Hz, RefTek-130G high-gain digitisers, and GPS timekeeping. Data from the RSISNE stations were complemented with data from the Institutos do Milênio project, which deployed a small network of 8 broadband stations in the province between 2007 and 2010 (times of operation at individual stations vary between a few months and a few years). The stations were equipped with GeoTech KS-2000 sensors, with flat response in velocity between 120s and 50Hz, GeoTech SMART-24 digitisers and GPS timekeeping. All stations recorded continuously at 100 Hz during their respective times of operation. The combined network considered in this study thus consists of 23 broadband stations, as shown in Figure 1.

Initial visual inspection of earthquakes at epicentral distances $\geq 88^\circ$ from the centre of the combined network and magnitude $m_b \geq 5.5$ yielded a database of 35 earthquakes of high signal-to-noise ratio, suitable for shear wave splitting analysis (Figure 2). S-wave phases from P-to-S conversions at the core-mantle boundary (i.e. SKS, PKS, and SKKS) were selected for shear wave splitting analysis, but direct S-wave arrivals were avoided because of associated problems such as source-side splitting and D'' grazing phases.

Shear wave splitting was analysed using the semi-automated approach of Teanby et al. (2004), which builds on the methodology of Silver and Chan (1991). Horizontal components are rotated and time shifted to minimise the second eigenvalue of the covariance matrix for particle motion of a time window around the shear wave arrival. This corresponds to linearizing the particle motion and usually reducing the tangential component energy, assuming the incoming S-wave is radially polarised before entering the anisotropic medium. In the approach of Silver and Chan (1991), a single shear-wave analysis window is picked manually. In the cluster analysis approach we adopt here, however, the splitting analysis is performed for a range of windows lengths and cluster analysis is utilised to find those measurements that are stable over many different windows (Teanby et al., 2004). Splitting measurements were made for 100 different windows, with data pre-filtered using a zero-phase Butterworth bandpass filter with corner frequencies 0.04–0.3 Hz. An example SKS-splitting measurements with clustering analysis is shown in Figure 3. Figure 4 shows an example of a null shear-wave splitting measurement for station NBMA. Note the lack of energy on the tangential component seismograms prior to correction for anisotropy. As discussed later in the manuscript, nulls indicate that either the mantle beneath the station is azimuthally isotropic, that the incoming shear wave energy was originally polarised perpendicular to, or parallel to the regional anisotropic fast direction or that depth dependent anisotropy has a cancelling effect on the splitting of the SKS phase (e.g., Barruol and Hoffmann, 1999).

4 Shear wave splitting results

The results obtained for SKS-splitting in the Borborema Province are summarised in Tables 1 and 2 and displayed in Figure 5. For some stations in the continental interior (NBMA, NBTA, NBPN) only null measurements are found, though it must be noted that earthquakes of only two, essentially orthogonal backazimuths constrain these results. At others, such as NBLI and PFBR in the continental interior, splitting delay times are <1 s. Elsewhere across the network splitting can be described as weak-to-moderate, with only three stations displaying $\delta t > 1.5$ s. Fast polarisation directions at stations NBLA, NBAN, NBRF, and NBPV towards the Atlantic rifted margin generally parallel the direction of plate motion at the time of Gondwana breakup. Variations in fast polarisation direction (ϕ) or the delay time (δt) are generally not identified in this study as a function of backazimuth at stations where we observe splitting (Figure 6); an exception to this is station NBPS, where ϕ and δt show variation, albeit for only two earthquakes. We thus adopted a stacking procedure based on the method of Restivo and Helffrich (1999) to obtain single pairs of splitting parameters for each station (Figure 7, Table 3). The stacking procedure was applied to all stations for which good quality individual measurements were obtained. The individual measurements and stacked results agree well (Tables 1 and 2; Figures 5 and 7). Note that the stacking procedure (and, equally, the

use of a single pair of splitting parameters at some stations) imposes the assumption that a single, horizontal, homogeneous layer of seismic anisotropy characterises the mantle beneath the station. We cannot preclude the possibility that this assumption is invalid, since our backazimuthal coverage of earthquakes is insufficient to resolve more complex dipping or multi-layer patterns of anisotropy (e.g., Silver and Savage, 1994; Hartog and Schwartz, 2000). For completeness, we include the results of four stations, CS6B, PDCB, RCBR, and TRSB, from the study of Assumpção et al. (2011) in Table 2, and Figures 5 and 7. Observations from Assumpção et al. (2011) are consistent with nearby stations from our study, with the exception of station PDCP, where the fast direction is almost perpendicular to nearby station NBCP. The NBCP/PDCP discrepancy is the only conclusive evidence we have in our study area for a complex (dipping or multi-layered) anisotropic fabric.

5 Discussion

Patterns of seismic anisotropy can develop due to the preferential alignment of minerals in the crust and/or mantle, the preferential alignment of fluid or melt, or some combination thereof (Blackman and Kendall, 1997). A range of plausible processes could lead to such anisotropy, including: (1) finite strain in the asthenosphere, generated by the mantle flow field, which is itself induced by a combination of buoyancy anomalies and plate-driven flow (e.g., Conrad et al., 2007; Conrad and Behn, 2010); (2) asthenospheric mantle flow, including that around deep cratonic keels (e.g., Bormann et al., 1993; Assumpção et al., 2006); and (3) a pre-existing fossil anisotropy frozen in the lithosphere (e.g., Silver and Chan, 1991; Plomerová and Babuska, 2010; Bastow et al., 2007). In the following sections, we discuss the implications of our observations for the lithospheric deformation history of the Borborema Province, and for present-day asthenospheric flow.

5.1 Anisotropy in the continental interior of the Borborema Province

The tectonic development of the Borborema Province spans a considerable portion of the geological record, from the Archean formation of cratonic nuclei, through the assembly of the Gondwana supercontinent in Neoproterozoic times, and the Mesozoic opening of the South Atlantic. The Province is considered by some workers to be a collage of accreted tectonic domains with distinct evolution, and separated by lithospheric-scale shear zones (e.g., Brito-Neves and Cordani, 1991; Cordani et al., 2003; Jardim de Sá et al., 1992). Such tectonic deformation, developed during the collisions of the Brasiliano/Pan-African orogeny, would be expected to have imprinted a strong anisotropic fabric on the lithospheric mantle. For example, plate-scale terrane boundaries that delineate the Paleoproterozoic Trans-Hudson Orogen in northern Canada are characterised by strong seismic anisotropic fossil fabrics, with fast polarisation directions

that parallel the strike of the suture between two Archean continental blocks (Bastow et al., 2011). The region apparently affected by the Trans-Hudson Orogen is also extremely broad (≥ 250 km wide). These observations, coupled with splitting delay times of $\delta t \geq 1$ s, were interpreted by Bastow et al. (2011) as evidence that the Trans Hudson Orogen was Himalayan in scale (e.g., St-Onge et al., 2006). Splitting delay times at many stations in the Borborema Province are markedly lower than in northern Canada: only null observations are found at stations NBTA and NBMA, while δt is relatively low at NBLI and PFBR. Larger delay times at stations NBPB and AGBR have associated ϕ values that do not parallel suture zone trends. It must be noted, however, that our backazimuthal coverage at many stations (e.g., NBMA, NBTA) is far from complete (Tables 1 and 2, Figures 5 and 6). Furthermore, our findings contrast with those reported for the Neoproterozoic Ribeira transpressional belt in SE Brazil, where fossil lithospheric anisotropy has been related to major transpressional shear zones. The Ribeira fabrics were postulated to combine with deeper asthenospheric flow to produce SKS splitting delays of > 2 s (Heinz et al. 2003; Assumpção et al. 2006). We thus explore potential explanations for our null/low δt observations tentatively.

The generally lower amounts of splitting observed in the heart of the Borborema Province compared to northern Canada may be consistent with the evolutionary model proposed by Neves (2003) and Neves et al. (2006), in which the shear zones that scar the region are the result of intra-plate deformation, focused by the localisation of heat-producing elements in the lithosphere (Neves et al., 2008). Vauchez et al., (1995) also conclude that the Borborema shear zones record intra plate deformation, while Tommasi et al. (1995) and Tommasi and Vauchez, (1997) have modeled the system as one of intraplate strain localisation in response to pre-existing, lateral variations in thermal-rheological plate structure. Deformation during the Brasiliano-Pan African orogeny may thus have been a relatively thin-skinned (crustal only) phenomenon, which would not have promoted the development of plate-scale anisotropic fabrics. This hypothesis would be consistent with the study of Van Schmus et al. (2008), who suggest on the basis of surface geological study that cratonic regions of NE Brazil have not been substantially internally altered by tectonic or magmatic activity since Palaeoproterozoic times. Support for the view that much of the anisotropy observed in our study is focused in the crust may come from local earthquake studies of shear wave splitting. do Nascimento et al. (2004), for example, examined local earthquakes of depth ≤ 5 km in the Borborema crust and found splitting delays, normalised to a path length of 1 km, of $\delta t \approx 1$ –28 ms per km. Assuming a crustal thickness of 30–35 km beneath the region (e.g., Luz et al., 2015a), and the persistence of upper-5 km anisotropic fabrics throughout the crust, we might thus expect our SKS phases to accrue up to 1 s of splitting in the crust alone – sufficient to explain many of our observations (Table 1). However, a recent study of electromagnetic data by Padilha et al. (2014) has found strong evidence in support of Neoproterozoic

subduction within the Province — a view supported by numerous recent studies (e.g., Fetter et al., 2003; Saraiva dos Santos et al., 2009; Amaral et al., 2011; Caxito et al., 2014). Specifically, they suggest that the Sobral and Senador Pompeu shear zones in the western part of the Borborema province were a suture/plate boundary during the Brasiliano orogeny, while the rest of the Borborema province was in an intraplate setting (Padhila, 2014). These studies likely render the thin-skinned hypothesis unlikely as an explanation for the results in the NW corner of our study area. Accordingly, stations NBPS and SBBR show fast polarisation directions sub-parallel to the local structural trends associated with this inferred suture (Figures 5 and 7).

In Cameroon, West Africa, which was connected to the Borborema Province until the Mesozoic breakup of the Atlantic, the Central African Shear Zone (CASZ) is also characterised by fossil lithospheric fabrics, with fast polarisation directions paralleling the strike of Mesozoic and older strike-slip faults (De Plaen et al., 2014). Intriguingly, in areas of the CASZ that have experienced magmatism associated with the 30 Ma–Present development of the Cameroon Volcanic Line (CVL), null SKS splitting measurements are found. De Plaen et al. (2014) invoked the lithospheric instability hypothesis of Fourrel et al. (2013) to explain this observation, with the low-volume but protracted removal of mantle lithosphere being the mechanism for melt generation along the line. Cenozoic volcanism in the Borborema Province may thus, if developed via a similar lithospheric instability mechanism, mark the timing of removal of some of the mantle lithospheric fabrics that developed during the Brasiliano/Pan-African orogeny. Cenozoic magmatism in Borborema is not particularly voluminous (Figure 1: e.g., de Oliveira and Medeiros, 2012), however, so is perhaps unlikely to be responsible for whole-scale erosion of anisotropic lithospheric mantle.

Alternatives to the isotropic mantle hypothesis exist for the Borborema Province, not least the possibility that our backazimuthal event coverage is insufficient to characterise anisotropic fabrics beneath the stations we classify here as null (Table 1 and Figure 5). Plastic deformation of peridotites usually results in the alignment of the [100] axis of olivine parallel to the direction of flow (e.g., Zhang and Karato, 1995; Bystricky et al., 2000; Tommasi et al., 2000); the apparent isotropy inferred from our SKS splitting analysis could also be the product of a horizontal flow-field in the event that olivine crystallographic orientations have b-type fabric (e.g., Vauchez et al., 2005; Bascou et al., 2008). However, this type of fabric is usually associated with hydrated, high-stress environments (e.g., the nose of the mantle wedge at some subduction zones Jung and Karato, 2001; Jung et al., 2006), so is unlikely to be an issue in the Brazilian continental interior. In any case, studies of mantle xenoliths and massifs indicate that isotropic upper mantle rocks are exceptional; a flowing asthenospheric mantle also cannot be isotropic (e.g., Vauchez et al., 2005). Geodynamical arguments may thus provide better

explanations for our observations. Null observations could be indicative of a two-layered model with orthogonal fast directions, as has been suggested, for example, at station CAN in Australia (Barruol and Hoffmann, 1999). For example, a shallow layer of shear-zone fossil anisotropy may be interfering with a deeper fabric associated with present-day mantle flow, perhaps small-scale convection, oriented perpendicular to the overlying lithospheric fabrics. Intriguingly, global viscous mantle flow models (e.g., Conrad et al., 2007) do predict N-S oriented mantle flow beneath the Borborema Province - perpendicular to many of the observed shear zones, and subparallel to one of the fast polarisation directions at station PDCB (Figures 5 and 7).

5.2 Anisotropy in the proximity of the South Atlantic Rifted Margin

The clearest evidence for shear wave splitting in the Borborema Province occurs under stations in the coastal regions of Brazil (e.g., NBCP, NBLA, NBAN, NBRF, NBPV: Figures 5 and 7), raising the possibility that Mesozoic continental breakup played a role in developing the observed anisotropic fabrics. In magma rich rifts such as Ethiopia, where extension occurs partly by rift-parallel dike intrusion, fast polarisation directions tend to be rift-parallel (e.g., Kendall et al., 2006; Bastow et al., 2010). In contrast, seismic anisotropy studies in magma-poor rifts such as Baikal (Gao et al., 1997) and the Rhine Graben (Vinnik et al., 1992), demonstrate rift perpendicular fast polarisation directions in response to the lattice preferred orientation of lithospheric mantle olivine crystals induced by plate stretching (Nicolas and Christensen, 1987).

The coast-perpendicular fast polarisation directions in Figures 5 and 7 may be due, in part, to the fossil anisotropic signature of plate stretching during Africa-South America breakup. Coast parallel observations in the north of the study area, at stations OCBR and NBCL, are also broadly consistent with the transform boundary tectonics that characterised the region during the Mesozoic. Closer observation indicates that splitting directions are parallel to the margin and oblique to the trace of transform faults in the Atlantic, which directly mark the ENE opening direction (Heine et al., 2013). The observed anisotropy near the coastal parts of our study area cannot, therefore, be linked unambiguously to the breakup process and our fast directions may, instead, be the result of earlier phases of lithospheric deformation. However, changes in rift kinematics during the development of continent-ocean transition are not uncommon, with analogue rifting modelling readily explaining the obliquity in Ethiopia between N40°E trending 30Ma border faults and the N20°E trending fault scarps in younger, rift-axial zones of Quaternary magmatism that are now thought to represent the final breakup boundary (e.g., Corti, 2008). Any hypothesis concerning continental breakup to explain our splitting directions would have the implication that the mantle lithosphere was deformed, but not destroyed during the development of continent-ocean transition.

5.3 Implications for present-day asthenospheric flow

Seismic anisotropic fabrics in Brazil have recently been explained by flow around the keel of deep-rooted cratons, such as around the Amazonian craton to the NW of our study area (e.g., Miller and Becker, 2012), and around the southern edge of the São Francisco craton to the south of our study area (e.g., Assumpção et al., 2006). Numerical predictions of global mantle flow from mantle convection models show that asthenospheric flow is oriented in the NS direction under the Borborema Province, rotating into a more NE-SW direction as it progresses towards the São Francisco craton (e.g., Conrad et al., 2007). Such a flow-field would be expected to be manifest as measurable anisotropic fabrics. Accordingly, just to the south of our study area, in SE Brazil, Heintz et al. (2003) observed large splitting delay times (>2.5 s), which they cited as evidence for a sub-lithospheric contribution to their results. Assumpção et al. (2006) favoured an asthenospheric flow hypothesis to explain their SKS splitting results in SE Brazil; Assumpção et al. (2011) also explained the N–S to NE–SW fast directions at stations RCBR and PDCB (Table 3 and Figures 5 and 7) in this way. However, our study reveals splitting delay times that are generally significantly smaller than those identified by Heintz et al. (2003) and Assumpção et al. (2011), so the case for a deep, asthenospheric anisotropic layer is far less compelling. Null and low δt observations across much of the Borborema Province imply the absence of a strong asthenospheric layer of anisotropy beneath the region, which would, in any case on the basis of Fresnel zone arguments (e.g., Alsina and Snieder, 1995), be expected to result in smooth variations in splitting parameters, not the relatively short wavelength variations observed in Figures 5 and 7. Our fast polarisation directions, where observed, also correlate poorly with the motion direction of the South American Plate (which varies depending on the reference frame assumed). This renders the “basal drag” hypothesis unlikely for our study area, though this may, in part, be due to the motion of the South American plate being too slow to develop significant anisotropic fabrics (e.g., Debayle and Ricard, 2013).

The null measurements across much of our network may imply a vertical flow of asthenospheric mantle due, for example, to the upward or downward limb of a small-scale convection cell (e.g., King and Anderson, 1998) induced at the edge of the São Francisco craton. Such a convection cell has been postulated to exist west of the north-south trending MQA magmatic alignment (Knesel et al., 2011). Thus, a combination of asthenospheric upwelling, and (to a lesser extent) thermal erosion or delamination of the lithosphere may have resulted in the replacement of a fossil lithospheric anisotropic signature in the SKS data with the low δt observations that dominate our results in the interior of the province. Again, however, the incomplete backazimuthal coverage at all of our stations means we cannot preclude the possibility that variations in ϕ and δt are the

complex result of two layers of seismic anisotropy. Nulls and low δt observations may be the result of orthogonal fast directions in the lithosphere and asthenosphere (e.g., station CAN in Australia: Barruol and Hoffmann, 1999). This is in contrast to the larger δt ($>2s$) observations in the Ribeira belt in SE Brazil, where lithospheric fabrics associated with major transpressional shear zones and deeper mantle fabrics have been suggested to combine constructively (Heinz et al. 2003; Assumpção et al. 2006).

6 Conclusions

Shear wave splitting parameters (ϕ , δt) from a broadband network of seismograph stations in NE Brazil reveal a lack of plate-scale anisotropic fabrics associated within the continental interior, perhaps supporting models of formation and evolution of the Borborema Province involving minimal deformation of the lithospheric mantle. Alternatively, delamination of anisotropic lithosphere during the development of Cenozoic volcanism may have eroded older fossil lithospheric fabrics, but the widespread Cenozoic magmatism required to achieve this is absent in the geological record, rendering the hypothesis unlikely. The apparently low levels of seismic anisotropy in the interior of the Borborema Province may thus be due to our incomplete backazimuthal event coverage. Variations in ϕ and δt may simply be the result of depth-dependent seismic anisotropy: nulls/low δt observations may be the subtractive result of orthogonal fast directions in the lithosphere and asthenosphere. At coastal stations near the South Atlantic rifted margin, however, splitting observations at some stations with δt up to 1.6s display fast polarisations that approximately parallel Mesozoic extension directions, consistent with passive margin development by plate stretching. The mantle lithosphere was thus deformed but not completely destroyed during the breakup of Gondwana. Nulls and low δt observations across much of the network may also indicate vertical flow from small-scale convection operating beneath the continent. However, there is no convincing evidence for the entrainment of present-day mantle flow, either due to absolute plate motion, or due to the deep cratonic root of the São Francisco craton.

7 Acknowledgments

This research was funded by the Instituto Nacional de Ciência e Tecnologia para Estudos Tectônicos (CNPq grant #57.3713/2008-1). IB also acknowledges funding from the Leverhulme Trust. JJ thanks CNPq for his research fellowship (CNPq, grant number 308171/2012-8). James Wookey is thanked for making his shear wave splitting codes publicly available. Maps were produced using the GMT mapping tools of Wessel et al. (2013). We thank Andrea Tommasi and an anonymous reviewer for insightful reviews that prompted us to think more deeply about the development of the Borborema Province and the importance of layered anisotropic models.

513

514

8 Table and Figure Captions

Table 1: Shear wave splitting parameters (fast polarisation direction, ϕ ; delay time, δt) for the Brazil network. σ_ϕ and $\sigma_{\delta t}$ are the 1σ errors associated with each measurement. BAZ: backazimuth; Δ : epicentral distance; ϕ fast polarisation direction.

Table 2: Null shear wave splitting observations.

Table 3: Stacked shear wave splitting parameters (fast polarisation direction, ϕ ; delay time, δt) for the Brazil network. σ_ϕ and $\sigma_{\delta t}$ are the 1σ errors associated with each measurement. BAZ: backazimuth; Δ : epicentral distance; ϕ fast polarisation direction; n : number of measurements. The splitting parameters in the lower half of the table are from the study of Assumpção et al. (2011).

Figure 1: Tectonic setting and broadband seismograph station locations (red triangles). The Borborema Province is bound to the west by the Paranaíba basin, and to the south by the São Francisco craton. Heavy grey lines are major shear zones. Dashed black lines are terrane boundaries. Tectonic information is from Vauchez et al. (1995). S.S.Z. – Sobral shear zone; S.P.S.Z. – Senador Pompeu shear zone; P.a.S.Z. – Patos shear zone; W.P.S.Z. – West Purnambuco shear zone; E.P.S.Z. – East Purnambuco shear zone; C.G.S.A. – Campina Grande shear zone. F.N.M.A. – Fernando de Noronha-Mecejana volcanic lineament; M.Q.A. – Macau-Queimadas volcanic lineament. Black stars are positions of Cenozoic magmatism reported in the study of de Oliveira and Medeiros (2012). APM: absolute plate motion from the HS3-Nuvel-1A model of Gripp and Gordon (2002) in the hotspot reference frame (red arrow) and the no-net rotation reference frame (black arrow).

Figure 2: The global distribution the earthquakes (orange circles) used in the study plotted with a Hammer map projection. The centre of the broadband network is marked by the star. Red lines are plate boundaries.

Figure 3: Example of a good shear wave splitting measurement for station NBRF: (a) original three components (east, north, and vertical) of the SKS phase and the selection window used; (b) radial and tangential components before and after the analysis was performed; observe that energy on the tangential component has been removed; (c) the top three images show the match between the fast dashed line and slow solid line waveform. The bottom two images show elliptical particle motion before (left), linearized after correction (right); (d) error and uncertainty calculation (contour labels indicate multiples of one sigma). Here a stable result and a well constrained 95% confidence contour (thick line) indicate a robust measurement; (e) measurements of ϕ and δt

obtained from 100 different analysis windows plotted against window number; (f) cluster analysis of splitting parameters obtained from the 100 windows. Good results are stable over a large number of windows.

Figure 4: Example of a null shear-wave splitting measurement for station NBMA: (a) radial and tangential components before and after the analysis was performed; (c) fast and slow waveforms and the linearisation of the particle motion. Note the lack of tangential component energy before and after analysis in (a), and the linear particle motion before and after analysis in (c).

Figure 5: Shear wave splitting parameters from the NE Brazil network (Tables 1 and 2). Stations without arrows displayed recorded only ‘Null’ measurements. APM: absolute plate motion from the HS3-Nuvel-1A model of Gripp and Gordon (2002) in the hotspot reference frame (red arrow) and the no-net rotation reference frame (black arrow). Tectonic/geological information are as per Figure 1.

Figure 6: The backazimuthal dependence of ϕ and δt across the network as displayed in Table 1 for stations with more than one pair of splitting parameters. Dashed vertical lines are the backazimuth of earthquakes that yielded null measurements (Table 2). Horizontal dotted lines are the stacked results shown in Table 3.

Figure 7: Stacked shear wave splitting parameters from the Brazil network. Stations without arrows recorded only null measurements. APM: absolute plate motion from the HS3-Nuvel-1A model of Gripp and Gordon (2002) in the hotspot reference frame (red arrow) and the no-net rotation reference frame (black arrow). Tectonic/geological information are as per Figure 1.

References

- Almeida, Y.B., J. Julià, and A. Frassetto (2015), Crustal architecture of the Borborema Province, NE Brazil, from receiver function CCP stacks: Implications for Mesozoic stretching and Cenozoic uplift, *Tectonophysics*, **649**, 68-80, doi:10.1016/j.tecto.2015.03.001.
- Alsina, D., and R. Snieder (1995), Small-scale sublithospheric mantle deformation: constraints from SKS splitting observations., *Geophys. J. Int.*, **123**, 431–448, doi:10.1111/j.1365-246X.1995.tb06864.x.
- Amaral, W., T. Santos, and E. Wernick (2011), Occurrence and geochemistry of metamafic rocks from the Forquilha Eclogite Zone, Central Ceará (NE Brazil): geodynamic implications, *Geol. J.*, **46**(2-3), 137–155, doi:10.1002/gj.1224.
- Artemieva, I., and W. Mooney (2001), Thermal thickness and evolution of Precambrian lithosphere: A global study, *J. Geophys. Res.*, **106** (B8), 16,387–16,414.
- Arthaud, M., R. Caby, R. Fuck, E. Dantas, and C. Parente (2008), Geology of the Northern Borborema Province NE Brazil and its Correlation with Nigeria, NW Africa, *Geol. Soc. Lond. Spec. Pub.*, **294**, 49–67.
- Assumpção, M., M. Heintz, A. Vauchez, and M. Silva (2006), Upper mantle anisotropy in SE and central Brazil from SKS splitting: Evidence of asthenospheric flow around a cratonic keel, *Earth Planet. Sci. Lett.*, **250**(1-2), 224–240, doi:10.1016/j.epsl.2006.07.038.
- Assumpção, M., M. Guarido, S. van der Lee, and J. Dourado (2011), Upper-mantle seismic anisotropy from SKS splitting in the South American stable platform: A test of asthenospheric flow models beneath the lithosphere, *Geol. Soc. Am.*, **3**(2), 173–180.
- Barruol, G., and R. Hoffmann (1999), Upper mantle anisotropy beneath the Geoscope stations, *J. Geophys. Res.*, **104** (B5), 10,757–10,773, doi:10.1029/1999JB900033.
- Bascou, J., G. Delpech, A. Vauchez, B. Moine, J. Cottin, and G. Barruol (2008), An integrated study of microstructural, geochemical, and seismic properties of the lithospheric mantle above the Kerguelen plume (Indian Ocean), *Geochem. Geophys. Geosyst.*, **9**(4), Q04036, doi:10.1029/2007GC001879.

- Bastow, I., T. Owens, G. Helffrich, and J. Knapp (2007), Spatial and temporal constraints on sources of seismic anisotropy: Evidence from the Scottish highlands, *Geophys. Res. Lett.*, **34**(5), L05305, doi:10.1029/2006GL028911.
- Bastow, I., S. Pilidou, J.-M. Kendall, and G. Stuart (2010), Melt-induced seismic anisotropy and magma assisted rifting in Ethiopia: evidence from surface waves, *Geochem. Geophys. Geosyst.*, **11**, Q0AB05, doi:10.1029/2010GC003036.
- Bastow, I., D. Thompson, J. Wookey, J. Kendall, G. Helffrich, D. Snyder, D. Eaton, and F. Darbyshire (2011), Precambrian plate tectonics: Seismic evidence from northern Hudson Bay, Canada, *Geology*, **39**(1), 91–94, doi:10.1130/G31396.1.
- Blackman, D., and J.-M. Kendall (1997), Sensitivity of teleseismic body waves to mineral texture and melt in the mantle beneath a mid-ocean ridge, *Phil. Trans. R. Soc. Lond.*, **355**, 217–231.
- Bormann, P., P.-T. Burghardt, L. Makeyeva, and L. Vinnik (1993), Teleseismic shear-wave splitting and deformations in Central Europe, *Phys. Earth Planet. Int.*, **78**(3), 157–166.
- Brito-Neves, B., and U. Cordani (1991), Tectonic evolution of South America during the late Proterozoic, *Precamb. Res.*, **53**(1), 23–40.
- Bystricky, M., K. Kunze, L. Burlini, and J.-P. Burg (2000), High shear strain of olivine aggregates: Rheological and seismic consequences, *Science*, **290** (5496), 1564–1567, doi:10.1126/science.290.5496.1564.
- Caxito, F., A. Uhlein, R. Stevenson, and G. Uhlein (2014), Neoproterozoic oceanic crust remnants in northeast Brazil, *Geology*, **42**(5), 387–390.
- Conrad, C., and M. Behn (2010), Constraints on lithosphere net rotation and asthenospheric viscosity from global mantle flow models and seismic anisotropy, *Geochem. Geophys. Geosyst.*, **11**(5), doi:10.1029/2009GC002970.
- Conrad, C., M. Behn, and P. Silver (2007), Global mantle flow and the development of seismic anisotropy: Differences between the oceanic and continental upper mantle, *J. Geophys. Res.*, **112**(B7), B07317, doi:10.1029/2006JB004608.

- Cordani, U., K. Sato, W. Teixeira, C. Tassinari, and M. Basei (2000), Crustal evolution of the South American platform, In: U.G. Cordani, E.J. Milani, A.T. Filho, D.A. Campos (Eds), Tectonic evolution of South America. Rio de Janeiro, pp. 19–40.
- Cordani, U., B. Brito-Neves, and M. D'Agrella-Filho (2003), From Rodinia to Gondwana: a review of the available evidence from South America, *Gondwana Res.*, **6**(2), 275–283, doi:10.1016/S1342-937X(05)70976-X.
- Corti, G. (2008), Control of rift obliquity on the evolution and segmentation of the main Ethiopian rift, *Nat. Geosci.*, **1** (4), 258–262, doi:10.1038/ngeo160.
- de Castro, D., W. Medeiros, E. Jardim de Sá, and J. Moreira (1998), Gravity map of part of Northeast Brazil and adjacent continental margin and its interpretation based on the hypothesis of isostasy, *Revista Brasileira de Geofísica*, **16**(2-3), 115–132.
- de Matos, R. (1992), The northeast Brazilian rift system, *Tectonics*, **11**(4), 766–791.
- de Oliveira, E., B. Windley, and M. Araújo (2010), The Neoproterozoic Sergipano orogenic belt, NE Brazil: A complete plate tectonic cycle in western Gondwana, *Precamb. Res.*, **181**(1), 64–84.
- de Oliveira, R., and W. Medeiros (2012), Evidences of buried loads in the base of the crust of Borborema Plateau (NE Brazil) from Bouguer admittance estimates, *J. S. Am. Earth Sci.*, **37**, 60–76.
- De Plaen, R., I. Bastow, E. Chambers, D. Keir, R. Gallacher, and J. Keane (2014), The development of magmatism along the Cameroon Volcanic Line: Evidence from seismicity and seismic anisotropy, *J. Geophys. Res.*, **119**, 4233–4252, doi: 10.1002/2013JB010583.
- Debayle, E., and Y. Ricard (2013), Seismic observations of large-scale deformation at the bottom of fast-moving plates, *Earth Planet. Sci. Lett.*, **376**, 165–177, doi: 10.1016/j.epsl.2013.06.025.
- do Nascimento, A., R. Pearce, and M. Takeya (2002), Local shear wave observations in João Câmara, northeast Brazil, *J. Geophys. Res.*, **107**(B10), 2232, doi: 10.1029/2001JB000560.
- do Nascimento, A., F. Bezerra, and M. Takeya (2004), Ductile Precambrian fabric control of seismic anisotropy in the Açú dam area, northeastern Brazil, *J. Geophys. Res.*, **109**(B10), B10311, doi:10.1029/2004JB003120.

- Fetter, A., T. Saraiva dos Santos, W. Van Schmus, P. Hackspacher, B. Bley de Brito
Neves, M. Arthaud, J. Nogueira Neto, and E. Wernick (2003), Evidence for
Neoproterozoic continental arc magmatism in the Santa Quitéria Batholith of Ceará State,
NW Borborema Province, NE Brazil: implications for the assembly of west Gondwana,
Gondwana Res., **6**(2), 265–273, doi:10.1016/S1342-937X(05)70975-8.
- Fouch, M., A. Fischer, E. Parmentier, M. Wyssession, and T. Clarke (2000), Shear wave
splitting, continental keels, and patterns of mantle flow, *J. Geophys. Res.*, **105**, 6255–
6276, doi:10.1029/1999JB900372.
- Fourel, L., L. Milelli, C. Jaupart, and A. Limare (2013), Generation of continental rifts,
basins, and swells by lithosphere instabilities, *J. Geophys. Res.*, **118**, 3080– 3100,
doi:10.1002/jgrb.50218.
- Ganade de Araujo, C., R. Weinberg, and U. Cordani (2014), Extruding the Borborema
Province (NE-Brazil): a two-stage Neoproterozoic collision process, *Terra Nova*, **26**(2),
157–168, doi:10.1111/ter.12084.
- Gao, S., P. Davis, H. Liu, P. Slack, A. Rigor, Y. Zorin, V. Mordvinova, V. Kozhevnikov,
and N. Logatchev (1997), SKS splitting beneath the continental rift zones, *J. Geophys.
Res.*, **102**, 22,781–22,797.
- Goodwin, A. (1996), Principles of Precambrian geology, 1-327 pp., Academic Press, San
Diego.
- Gripp, A., and R. Gordon (2002), Young tracks of hotspots and current plate velocities,
Geophys. J. Int., **150**(2), 321–361, doi:10.1046/j.1365-246X.2002.01627.x.
- Hartog, R., and S. Schwartz (2000), Subduction-induced strain in the upper mantle east of
the Mendocino triple junction, California, *J. Geophys. Res.*, **105**, 7909–7930.
- Heine, C., J. Zoethout, and R. D. Mueller (2013), Kinematics of the South Atlantic rift,
Solid Earth, **4**, 215–253.
- Heintz, M., A. Vauchez, M. Assumpção, G. Barruol, and M. Egydio-Silva (2003), Shear
wave splitting in SE Brazil: an effect of active or fossil upper mantle flow, or both?,
Earth Planet. Sci. Lett., **211**(1), 79–95.

- Jardim de Sá, E., M. Macedo, R. Fuck, and K. Kawashita (1992), Terrenos Proterozóicos na província Borborema ea Margem Norte do Gráton São Francisco, *Revista Brasileira de Geociências*, **22**(4), 472–480.
- Jung, H., and S-I. Karato (2001), Water-induced fabric transitions in olivine, *Science*, **293**(5534), 1460–1463.
- Jung, H., I. Katayama, Z. Jiang, T. Hiraga, and S-I. Karato (2006), Effect of water and stress on the lattice-preferred orientation of olivine, *Tectonophysics*, **421**(1), 1–22.
- Kaminski, E., and N. Ribe (2002), Timescales for the evolution of seismic anisotropy in mantle flow, *Geochem. Geophys. Geosyst.*, **3**(8), 1–17.
- Kendall, J.-M., S. Pilidou, D. Keir, I. Bastow, G. Stuart, and A. Ayele (2006), Mantle upwellings, melt migration and the rifting of Africa: Insights from seismic anisotropy, in The Afar Volcanic Province within the East African Rift System, eds. Yirgu, G. Ebinger, C.J. & Maguire, P.K.H., *Geol. Soc. Lond. Spec. Pub.*, **259**, 271–293.
- King, S., and D. Anderson (1998), Edge-driven convection, *Earth Planet. Sci. Lett.*, **160**, 289–296.
- King, S., and J. Ritsema (2000), African hot spot volcanism: small-scale convection in the upper mantle beneath cratons, *Science*, **290**, 1137–1140.
- Knesel, K., Z. Souza, P. Vasconcelos, B. Cohen, and F. Silveira (2011), Young volcanism in the Borborema Province, NE Brazil, shows no evidence for a trace of the Fernando de Noronha plume on the continent, *Earth Planet. Sci. Lett.*, **302**(1), 38–50, doi:10.1016/j.epsl.2010.11.036.
- Lima, M.V.A.G., J. Berrocal, J.E.P. Soares, R.A. Fuck (2015), Deep seismic refraction experiment in northeast Brazil: New constraints for Borborema Province evolution. *J. S. Am. Earth Sci.* **58**, 335–349.
- Long, M., and P. Silver (2009), Shear Wave Splitting and Mantle Anisotropy: Measurements, Interpretations, and New Directions, *Surveys in Geophysics*, **30**(4), 407–461.
- Luz, R.M.N., J. Julià, and A.F. do Nascimento (2015a), Bulk crustal properties of the Borborema Province, NE Brazil, from P-wave receiver functions: Implications for models of intraplate Cenozoic uplift, *Tectonophysics*, doi:10.1016/j.tecto.2014.12.017.

- Luz, R.M.N., J. Julià, and A.F. do Nascimento (2015b), Crustal structure of the eastern Borborema Province, NE Brazil, from the joint inversion of receiver functions and surface wave dispersion: Implications for plateau uplift, *J. Geophys. Res.*, **120**, doi:10.1002/2015JB011872.
- Miller, M., and T. Becker (2012), Mantle flow deflected by interactions between subducted slabs and cratonic keels, *Nat. Geosci.*, **5** (726-731), doi:10.1038/NGEO1553.
- Mizusaki, A., A. Thomaz-Filho, E. Milani, and P. De Césaro (2002), Mesozoic and Cenozoic igneous activity and its tectonic control in northeastern Brazil, *J. S. Am. Earth Sci.*, **15**(2), 183–198.
- Morais Neto, J., K. Hegarty, G. Karner, and F. Alkmim (2009), Timing and mechanisms for the generation and modification of the anomalous topography of the Borborema Province, northeastern Brazil, *Marine Petrol. Geol.*, **26**(7), 1070–1086.
- Neves, S. (2003), Proterozoic history of the Borborema province (NE Brazil): Correlations with neighboring cratons and Pan-African belts and implications for the evolution of western Gondwana, *Tectonics*, **22**(4), 1031, doi:10.1029/2001TC001352.
- Neves, S., O. Bruguier, A. Vauchez, D. Bosch, J. da Silva, and G. Mariano (2006), Timing of crust formation, deposition of supracrustal sequences, and Transamazonian and Brasiliano metamorphism in the East Pernambuco belt (Borborema Province, NE Brazil): Implications for western Gondwana assembly, *Precamb. Res.*, **149**(3), 197–216, doi:10.1016/j.precamres.2006.06.005.
- Neves, S., A. Tommasi, A. Vauchez, and R. Hassani (2008), Intraplate continental deformation: influence of a heat-producing layer in the lithospheric mantle, *Earth Planet. Sci. Lett.*, **274**(3), 392–400, doi:10.1016/j.epsl.2008.07.040.
- Nicolas, A., and N. Christensen (1987), Formation of anisotropy in upper mantle peridotites—A review, Composition, structure and dynamics of the lithosphere–asthenosphere system, **16**, 111–123, doi:10.1029/GD016p0111.
- Padilha, A., I. Vitorello, M. Pádua, and M. Bologna (2014), Electromagnetic constraints for subduction zones beneath the northwest Borborema province: Evidence for neoproterozoic island arc–continent collision in northeast Brazil, *Geology*, **42**(1), 91–94.

- Plomerová, J., and V. Babuska (2010), Long memory of mantle lithosphere fabric–European LAB constrained from seismic anisotropy, *Lithos*, doi: 10.1016/j.lithos.2010.01.008.
- Polet, J., and D. Anderson (1995), Depth extent of cratons as inferred from tomographic studies, *Geology*, **23**(3), 205–208.
- Restivo, A., and G. Helffrich (1999), Teleseismic shear wave splitting measurements in noisy environments, *Geophys. J. Int.*, **137**(3), 821–830, doi:10.1046/j.1365246x.1999.00845.x.
- Santos, T., A. Fetter, and J. N. Neto (2008), Comparisons between the northwestern Borborema province, NE Brazil, and the southwestern Pharusian Dahomey belt, SW Central Africa, *Geol. Soc. Lond. Spec. Pub.*, **294**(1), 101–120.
- Santos, A. C. L., A. L. Padilha, R. A. Fuck, A. C. B. Pires, I. Vitorello, and M. B. Pádua (2014), Deep structure of a stretched lithosphere: Magnetotelluric imaging of the southeastern Borborema Province, NE Brazil, *Tectonophysics*, **610**, 39–50.
- Saraiva dos Santos, T., M. Garcia, W. Amaral, R. Caby, E. Wernick, M. Arthaud, E. Dantas, and M. Santosh (2009), Relics of eclogite facies assemblages in the Ceará Central Domain, NW Borborema Province, NE Brazil: implications for the assembly of West Gondwana, *Gondwana Res.*, **15**(3), 454–470, doi: 10.1016/j.gr.2009.01.003.
- Savage, M. (1999), Seismic anisotropy and mantle deformation: What have we learned from shear wave splitting?, *Rev. Geophys.*, **37**, 65–106.
- Silver, P. (1996), Seismic anisotropy beneath the continents: probing the depths of geology, *Annu. Rev. Earth Planet. Sci.*, **24**, 385–432.
- Silver, P., and G. Chan (1991), Shear wave splitting and subcontinental mantle deformation, *J. Geophys. Res.*, **96**(B10), 16,429–16,454, doi:10.1029/91JB00899.
- Silver, P., and W. Chan (1988), Implications for continental structure and evolution from seismic anisotropy, *Nature*, **335**, 6185, doi:10.1038/335034a0.
- Silver, P., and M. Savage (1994), The interpretation of shear wave splitting parameters in the presence of two anisotropic layers, *Geophys. J. Int.*, **119**, 949–963.

- Sleep, N. (2003), Survival of Archean cratonal lithosphere, *J. Geophys. Res.*, **108**(B6), 2302, doi:10.1029/2001JB000169.
- Sleep, N., C. Ebinger, and J.-M. Kendall (2002), Deflection of mantle plume material by cratonic keels, *J. Geol. Soc. Lond.*, **199**, 135–150.
- Soares, J., M. de Lima, R. Fuck, and J. Berrocal (2010), Características sísmicas da litosfera da Província Borborema: Resultados parciais do experimento de refração sísmica profunda, in IV Simpósio Brasileiro de Geofísica.
- St-Onge, M., M. Searle, and N. Wodicka (2006), Trans-Hudson Orogen of North America and Himalaya-Karakoram-Tibetan Orogen of Asia: Structural and thermal characteristics of the lower and upper plates, *Tectonics*, **25**(4), doi:10.1029/2005TC001907.
- Teanby, N., J.-M. Kendall, and M. Van der Baan (2004), Automation of shear-wave splitting measurements using cluster analysis, *Bull. Seis. Soc. Am.*, **94**(2), 453–463, doi:10.1785/0120030123.
- Tommasi, A., and A. Vauchez (1997), Complex tectono-metamorphic patterns in continental collision zones: the role of intraplate rheological heterogeneities, *Tectonophysics*, **279**, 327–350.
- Tommasi, A., A. Vauchez, and B. Daudré (1995), Initiation and propagation of shear zones in a heterogeneous continental lithosphere, *J. Geophys. Res.*, **100** (B11), 22,083–22,101.
- Tommasi, A., D. Mainprice, G. Canova, and Y. Chastel (2000), Viscoplastic selfconsistent and equilibrium-based modeling of olivine lattice preferred orientations: Implications for the upper mantle seismic anisotropy, *J. Geophys. Res.*, **105**(B4), 7893–7908, doi:10.1029/1999JB900411.
- Trompette, R., and A. Carozzi (1994), Geology of Western Gondwana (2000-500 Ma): Pan-African-Brasiliano Aggregation of South America and Africa, 350pp., Balkema Rotterdam.
- Van Schmus, W., E. Oliveira, A. Da Silva Filho, S. Toteu, J. Penaye, and I. Guimaraes (2008), Proterozoic links between the Borborema Province, NE Brazil, and the Central African Fold Belt, *Geol. Soc. Lond. Spec. Pub.*, **294**, 69–99, doi: 10.1144/SP294.5.

- 897
898 Van Schmus, W., M. Kozuch, and B. de Brito Neves (2011), Precambrian history of the
899 Zona Transversal of the Borborema Province, NE Brazil: insights from Sm–Nd and U–Pb
900 geochronology, *J. S. Am. Earth Sci.*, **31**(2), 227–252.
901
- 902 Vauchez, A., and M. da Silva (1992), Termination of a continental-scale strike-slip fault
903 in partially melted crust: The West Pernambuco shear zone, northeast Brazil, *Geology*,
904 **20**(11), 1007–1010.
905
- 906 Vauchez, A., and A. Nicolas (1991), Mountain building: strike-parallel motion and
907 mantle anisotropy, *Tectonophysics*, **185**(3-4), 183–201, doi:10.1016/0040-
908 1951(91)90443-V.
909
- 910 Vauchez, A., S. Neves, R. Caby, M. Corsini, M. Egydio-Silva, M. Arthaud, and V.
911 Amaro (1995), The Borborema shear zone system, NE Brazil, *J. S. Am. Earth Sci.*, **8**(3),
912 247–266.
913
- 914 Vauchez, A., F. Dineur, and R. Rudnick (2005), Microstructure, texture and seismic
915 anisotropy of the lithospheric mantle: Insights from the Labait volcano xenoliths
916 (Tanzania), *Earth Planet. Sci. Lett.*, **232**, 295–314, doi:10.1016/j.epsl.2005.01.024.
917
- 918 Vauchez, A., A. Tommasi, and D. Mainprice (2012), Faults (shear zones) in the Earth's
919 mantle, *Tectonophysics*, **558**, 1–27, doi:10.1016/j.tecto.2012.06.006.
920
- 921 Vinnik, L., V. Farra, and B. Romanowicz (1989), Azimuthal anisotropy in the Earth from
922 observations of SKS at Geoscope and NARS broadband stations, *Bull. Seis. Soc. Am.*,
923 **79**(5), 1542–1558.
924
- 925 Vinnik, L., L. Makeyeva, A. Milev, and A. Usenko (1992), Global patterns of azimuthal
926 anisotropy and deformation in the continental mantle, *Geophys. J. Int.*, **111**, 433–447.
927
- 928 Wessel, P., W. Smith, R. Scharroo, J. Luis, and F. Wobbe (2013), Generic mapping tools:
929 Improved version released, *EOS Trans. AGU*, **94**(45), 409–410, doi:
930 10.1002/2013EO450001.
931
- 932 Zhang, S., and S.-I. Karato (1995), Lattice preferred orientation of olivine aggregates
933 deformed in simple shear, *Nature*, **375**, 774–777, doi:10.1038/375774a0.

Table 1:

Station	Station Lat./Lon.	Event Lat./Lon.	BAZ, deg	Δ , deg	ϕ , deg	σ_ϕ , deg	δt , s	$\sigma_{\delta t}$, s	Phase
AGBR	-8.43/-35.94	-21.98/-179.54	229	133	-62	9.75	1.47	0.19	PKS
GRBR	-8.23/-35.64	-15.22/-172.57	241	131	62	4.00	0.96	0.16	PKS
		-20.71/-174.04	234	130	62	6.00	0.99	0.19	PKS
		-21.61/-179.53	229	134	-90	10.00	0.93	0.12	SKS
		-23.78/179.76	227	133	54	5.50	1.17	0.12	PKS
NBAN	-9.67/-36.28	-18.68/-174.71	236	130	-60	10.25	1.08	0.16	PKS
		51.84/95.91	33	123	-58	3.25	1.41	0.13	SKS
		52.17/-171.71	328	124	-57	7.00	1.74	0.20	SKKS
NBCL	-4.22/-38.29	-18.68/-174.71	241	131	-66	18.75	0.60	0.26	PKS
NBCP	-12.59/-39.18	-24.98/178.52	224	128	-42	3.00	1.92	0.13	SKS
NBLA	-10.99/-37.79	-17.95/167.23	221	142	-63	8.75	1.44	0.31	SKKS
		49.41/155.91	346	140	-51	15.00	1.02	0.16	PKS
		57.60/163.20	345	131	-34	4.25	1.02	0.04	PKS
NBLI	-7.36/-36.95	-18.68/-174.71	238	131	-43	9.50	1.02	0.33	PKS
		-23.78/179.76	228	133	-58	11.50	0.99	0.31	PKS
		49.80/145.06	358	138	-69	11.25	1.17	0.43	SKKS
NBPA	-5.75/-37.11	-18.68/-174.71	239	132	-48	9.50	0.54	0.16	PKS
NBPB	-5.54/-39.58	51.84/95.91	30	121	89	8.75	1.53	0.14	SKS
NBPS	-4.39/-41.45	-23.78/179.76	233	131	58	7.50	0.96	0.27	PKS
		51.84/95.91	29	121	-90	6.00	1.59	0.17	SKS
NBPV	-6.42/-35.29	-18.68/-174.71	237	133	51	7.25	1.20	0.36	PKS
NBRF	-8.68/-35.13	-18.68/-174.71	235	132	-68	16.75	0.96	0.18	PKS
		-21.61/-179.53	229	134	86	2.50	1.41	0.04	SKS
		49.53/-126.89	319	98	82	7.75	1.17	0.13	SKS
OCBR	-4.58/-38.39	-17.34/-177.31	241	134	-68	7.50	1.29	0.15	PKS
		-25.77/179.53	229	132	-60	6.00	1.23	0.22	PKS
PFBR	-6.12/-38.27	-1.48/99.49	99	137	22	2.25	0.84	0.11	PKS
		45.16/137.45	5	141	7	3.50	1.35	0.11	SKKS
		54.20/154.32	350	131	0	2.25	0.78	0.10	PKS
SABR	-8.35/-36.55	-23.78/179.76	227	132	-57	6.75	1.17	0.28	PKS
		54.20/154.32	349	128	49	9.00	0.75	0.11	PKS

Table 1:

Station	Station Lon/Lat	BAZ	Event Lat/Lon
BEBR	-38.29/-4.42	62	28.78/63.95
		96	-0.72/99.87
GRBR	-35.64/-8.23	216	-34.34/179.87
		329	52.17/-171.71
NBAN	-36.28/-9.67	229	-21.61/-179.53
NBCL	-38.29/-4.22	347	49.41/155.91
		231	-23.78/179.76
		357	49.80/145.06
NBCP	-39.18/-12.59	221	-17.83/167.13
		222	-17.38/167.28
		221	-17.95/167.23
NBIT	-39.43/-14.93	223	-14.66/167.34
NBLI	-36.95/-7.36	329	52.17/-171.71
		329	52.17/-171.71
NBMA	-38.76/-7.36	239	-18.68/-174.71
		229	-23.78/179.76
		229	-23.78/179.76
NBPA	-37.11/-5.75	229	-23.78/179.76
		229	-23.78/179.76
		329	52.17/-171.71
NBPB	-39.58/-5.54	234	-21.61/-179.53
NBPN	-40.20/-10.85	224	-17.83/167.13
		224	-17.38/167.28
		355	49.80/145.06
NBPV	-35.29/-6.42	228	-23.78/179.76
NBTA	-38.06/-9.12	228	-23.78/179.76
		328	52.17/-171.71
		328	52.17/-171.71

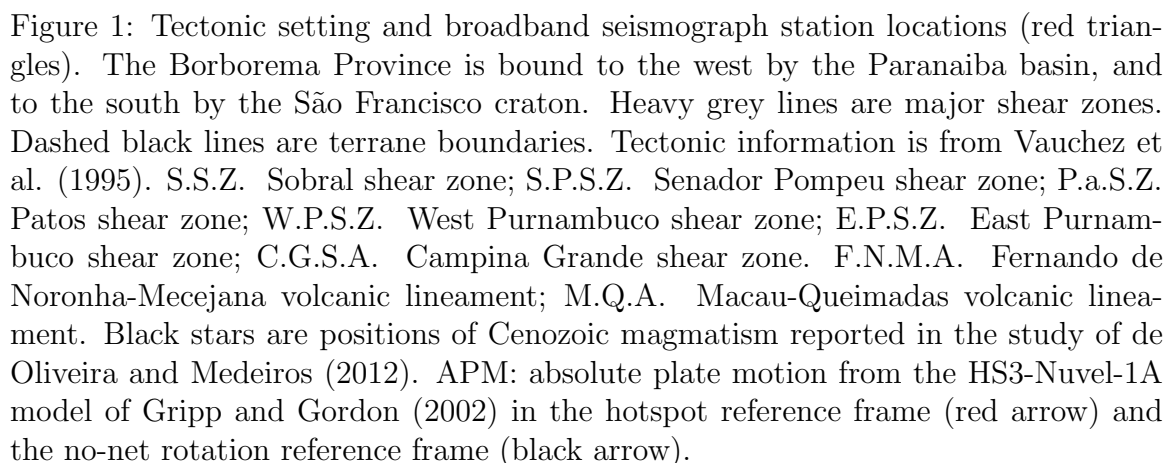
continued on next page

Table 1: continued

Station	Station Lon/Lat	BAZ	Event Lat/Lon
OCBR	-38.39/-4.58	319	49.53/-126.89
		231	-21.61/-179.53
		231	-21.61/-179.53
		80	11.01/91.82
		351	53.88/152.89
		346	50.97/157.58
		350	54.20/154.32
PFBR	-38.27/-6.12	346	46.86/155.15
		346	50.97/157.58
		230	-23.78/179.76
		237	-20.71/-174.04
SABR	-36.55/-8.35	80	13.20/93.09
		101	-1.48/99.49
SBBR	-40.37/-3.74	319	49.53/-126.89
SLBR	-35.74/-6.78	221	-22.35/170.63
		81	11.01/91.82
		237	-17.34/-177.31
		81	11.06/91.81
		225	-25.77/179.53
		234	-21.86/-173.82
		243	-15.21/-172.37

Table 1:

Station	Lat/Lon	ϕ , deg	σ_ϕ , deg	δt , s	$\sigma_{\delta t}$, s	n
AGBR	-35.94/-8.43	-61	9.75	1.5	0.2	1
GRBR	-35.64/-8.23	62	1.25	1.05	0.05	4
NBAN	-36.28/-9.67	-61	3.5	1.2	0.09	3
NBCL	-38.29/-4.22	-65	18.75	0.63	0.26	1
NBCP	-39.18/-12.59	-41	3	1.95	0.13	1
NBLA	-37.79/-10.99	-69	1.5	1.11	0.03	3
NBLI	-36.95/-7.36	-60	3.5	0.72	0.07	3
NBPA	-37.11/-5.75	-47	9.5	0.57	0.16	1
NBPB	-39.58/-5.54	90	8.75	1.56	0.14	1
NBPS	-41.45/-4.39	58	2.5	1.05	0.13	2
NBPV	-35.29/-6.42	52	7.25	1.23	0.36	1
NBRF	-35.13/-8.68	86	2.75	1.38	0.04	3
OCBR	-38.39/-4.58	-59	3	1.35	0.11	2
PFBR	-38.27/-6.12	31	4.25	0.6	0.04	3
SABR	-36.55/-8.35	-56	6.75	1.2	0.28	1
SBBR	-40.37/-3.74	50	9	0.78	0.11	1
Constraints from the study of Assumpcao et al. (2011).						
CS6B	-36.671/-5.494	-	-	-	-	-
PDCB	-39.12/-12.53	33	11	1	0.3	4
RCBR	-35.90/-5.83	9	11	1.9	0.2	9
TRSB	-42.71/4.87	105	20	0.8	0.3	9



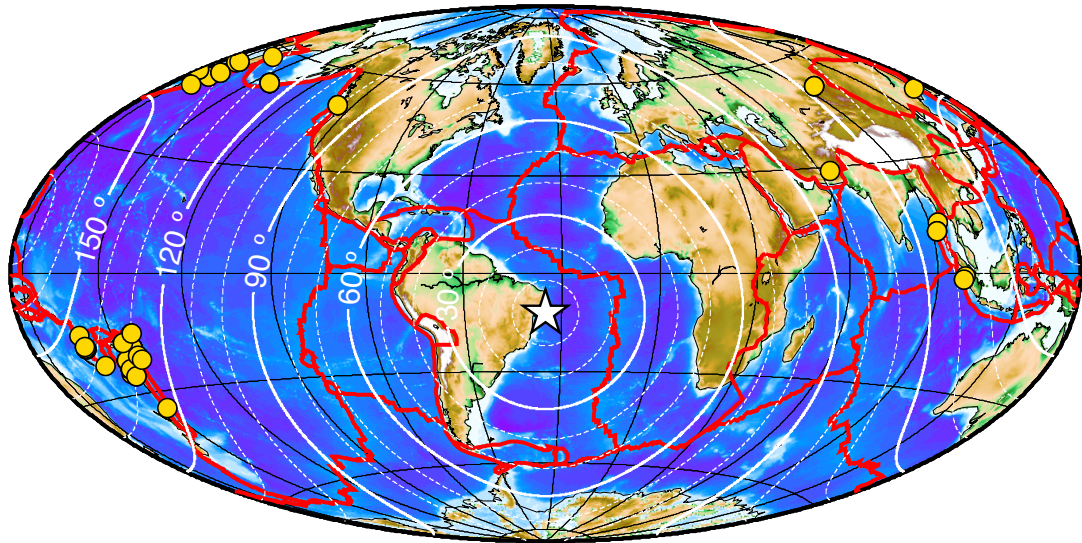


Figure 2: The global distribution the earthquakes (orange circles) used in the study plotted with a Hammer map projection. The centre of the broadband network is marked by the star. Red lines are plate boundaries.

Station: NBRF $\Delta=134^\circ$ BAZ=229° Lat: 21.61°S Lon: 179.53°E Depth: 644km

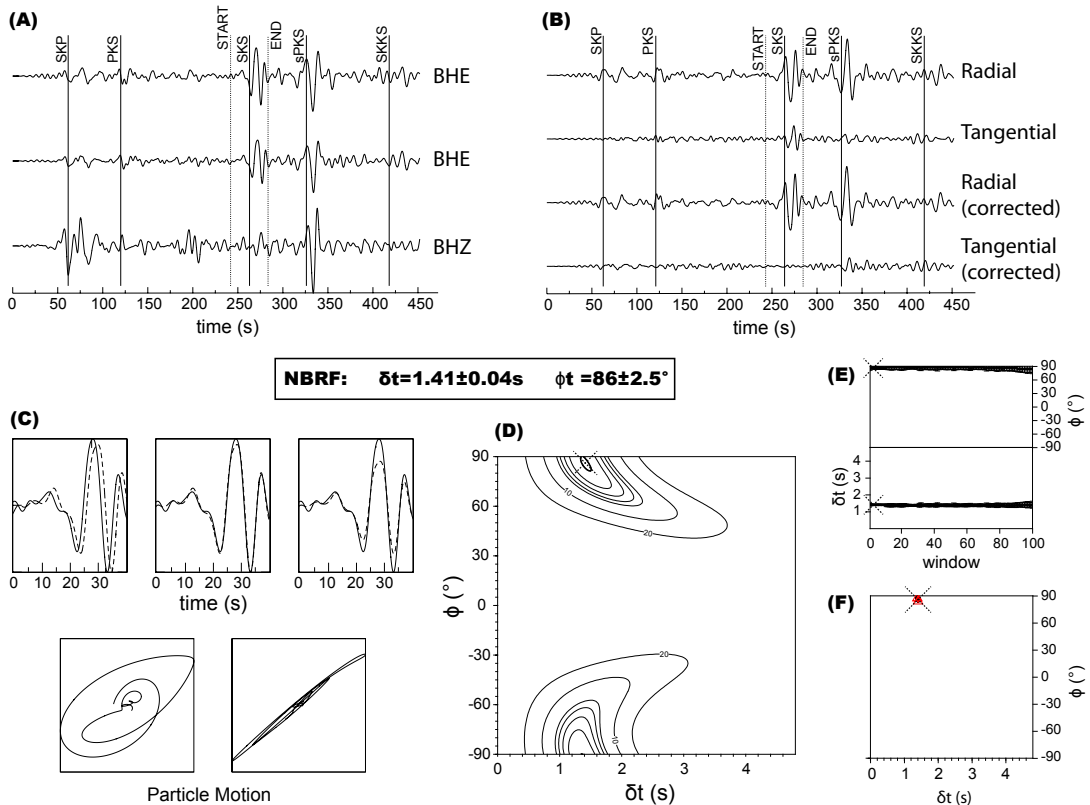
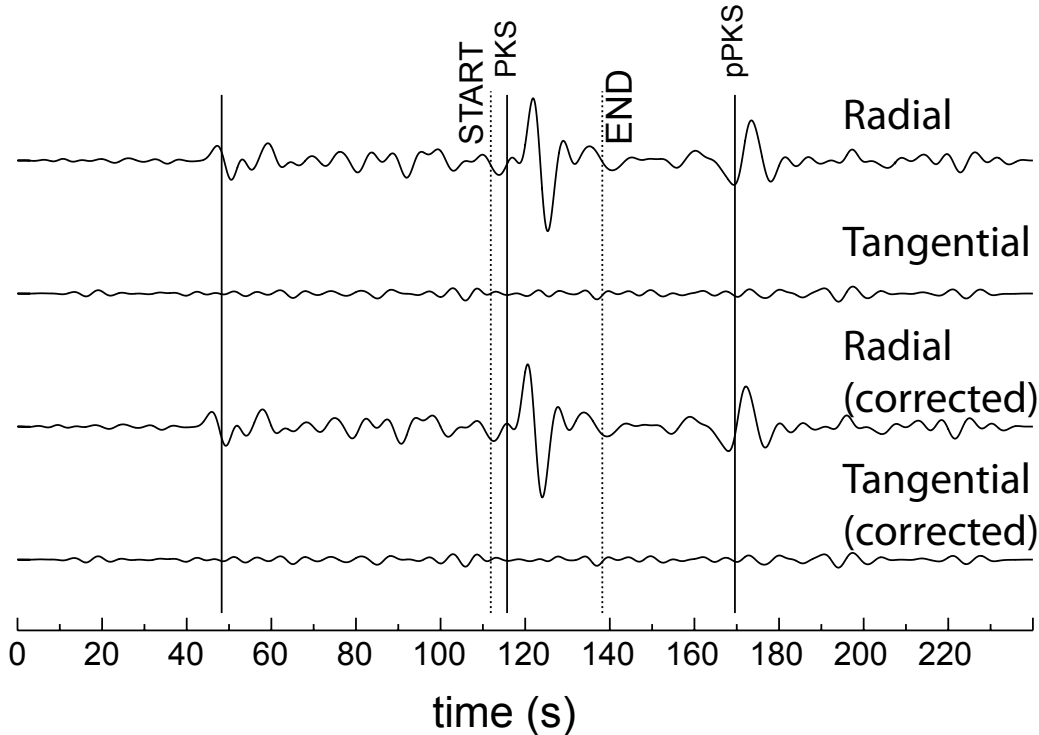
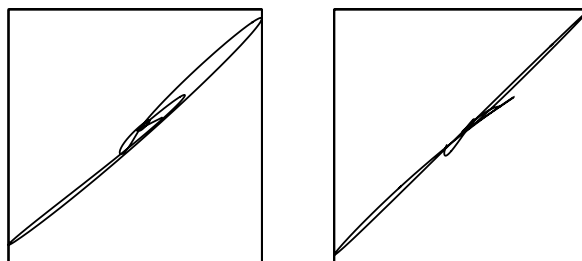
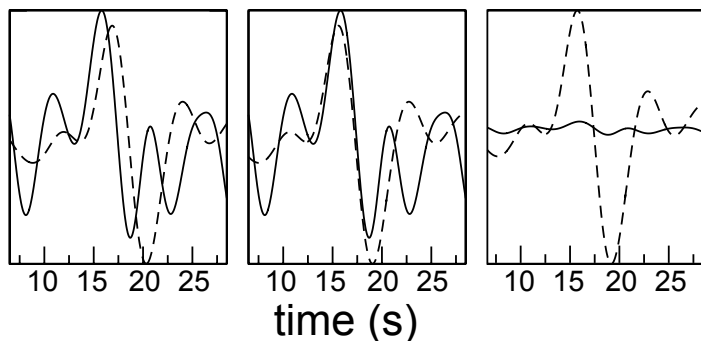


Figure 3: Example of a good shear wave splitting measurement for station NBRF: (a) original three components (east, north, and vertical) of the SKS phase and the selection window used; (b) radial and tangential components before and after the analysis was performed; observe that energy on the tangential component has been removed; (c) the top three images show the match between the fast dashed line and slow solid line waveform. The bottom two images show elliptical particle motion before (left), linearized after correction (right); (d) error and uncertainty calculation (contour labels indicate multiples of one sigma). Here a stable result and a well constrained 95% confidence contour (thick line) indicate a robust measurement; (e) measurements of ϕ and δt obtained from 100 different analysis windows plotted against window number; (f) cluster analysis of splitting parameters obtained from the 100 windows. Good results are stable over a large number of windows.



Station: NBMA $\Delta=129^\circ$ BAZ= 239°
Lat: 18.68°S Lon: 178.71°W Depth: 134km



Particle Motion

Figure 4: Example of a null shear-wave splitting measurement for station NBMA: (a) radial and tangential components before and after the analysis was performed; (c) fast and slow waveforms and the linearisation of the particle motion. Note the lack of tangential component energy before and after analysis in (a), and the linear particle motion before and after analysis in (c).

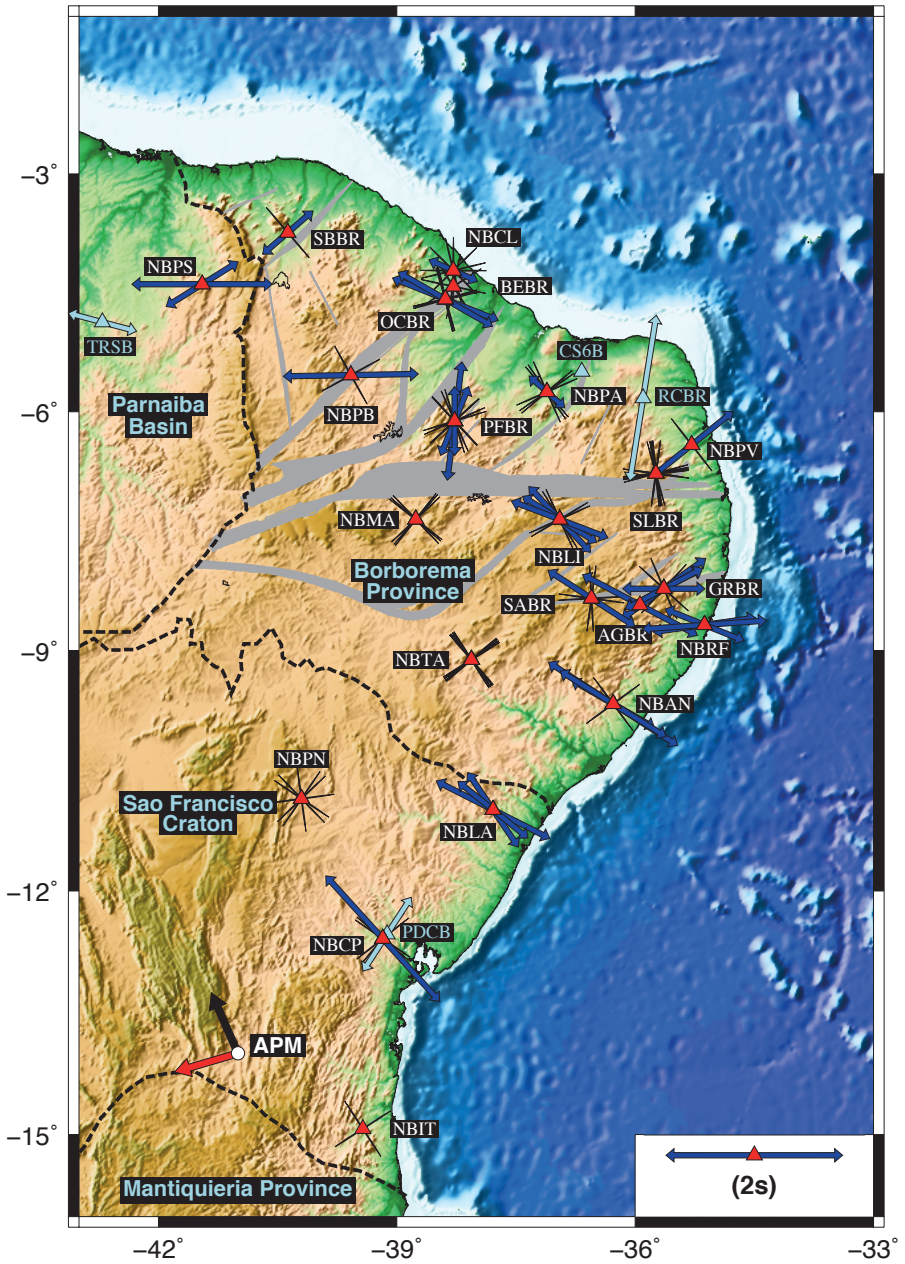


Figure 5: Shear wave splitting parameters from the NE Brazil network (Tables 1 and 2). Stations without arrows displayed recorded only ‘Null’ measurements. APM: absolute plate motion from the HS3-Nuvel-1A model of Gripp and Gordon (2002) in the hotspot reference frame (red arrow) and the no-net rotation reference frame (black arrow). Tectonic/geological information are as per Figure 1.

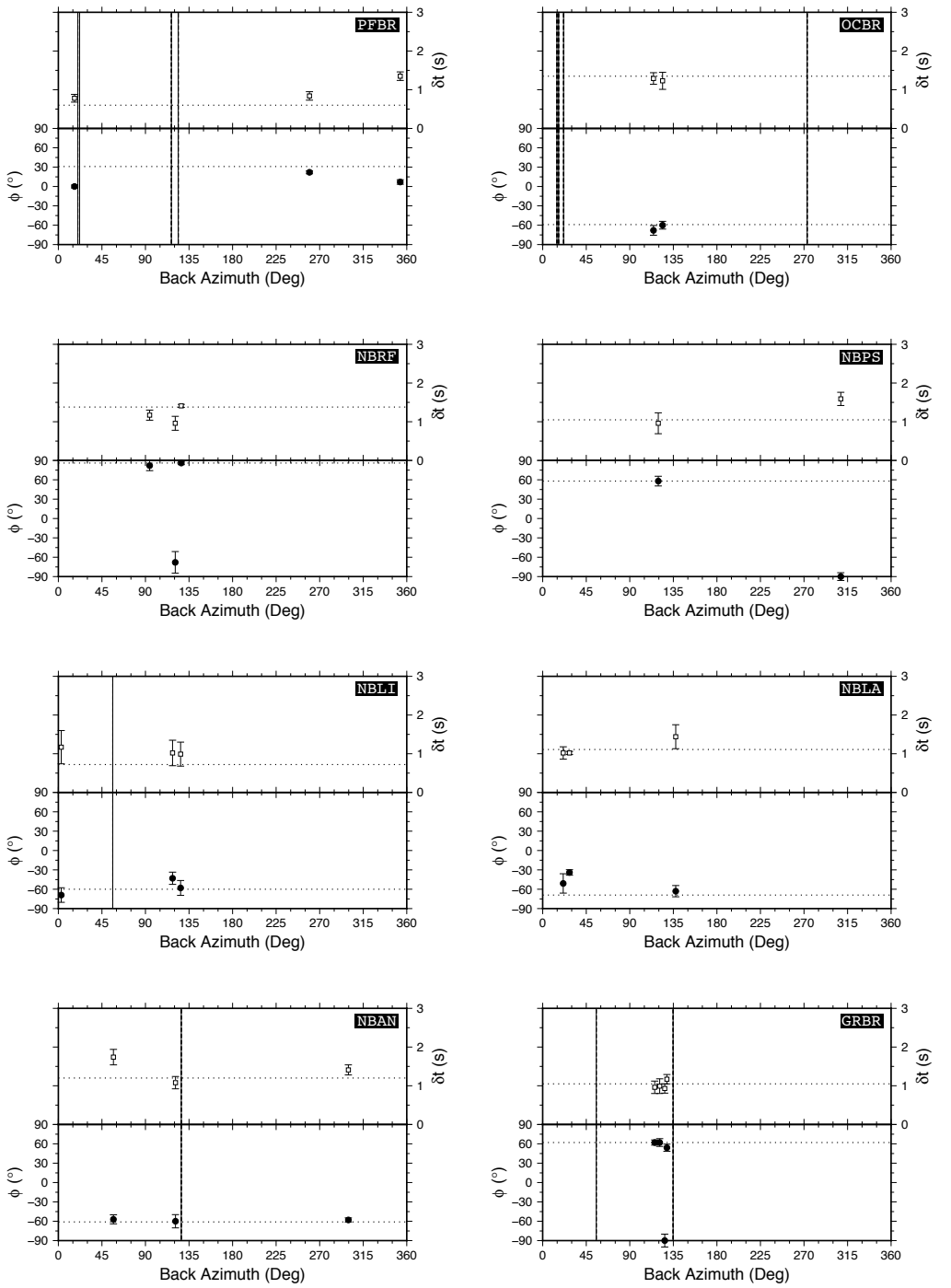


Figure 6: The backazimuthal dependence of ϕ and δt across the network as displayed in Table 1 for stations with more than one pair of splitting parameters. Dashed vertical lines are the backazimuth of earthquakes that yielded null measurements (Table 2). Horizontal dotted lines are the stacked results shown in Table 3.

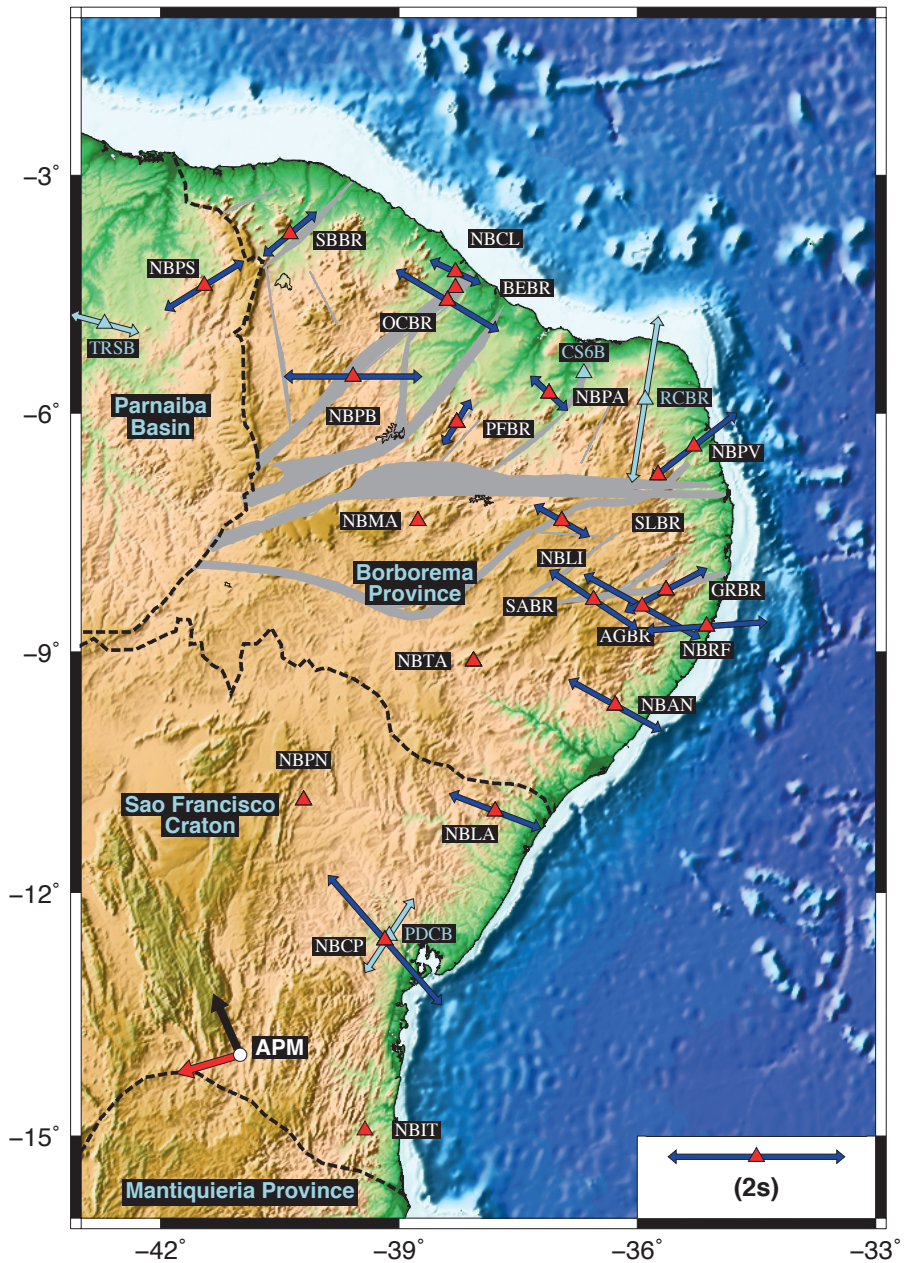


Figure 7: Stacked shear wave splitting parameters from the Brazil network. Stations without arrows recorded only null measurements. APM: absolute plate motion from the HS3-Nuvel-1A model of Gripp and Gordon (2002) in the hotspot reference frame (red arrow) and the no-net rotation reference frame (black arrow). Tectonic/geological information are as per Figure 1.