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Upper mantle anisotropy in SE and Central Brazil from SKS splitting: Evidence of asthenospheric flow around a cratonic keel

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Abstract

We present results of upper mantle anisotropy derived from measurements of core refracted shear wave splitting (mainly SKS phases) recorded at 48 stations covering the major tectonic provinces in Central and SE Brazil, such as the Tocantins Province (Paraguay–Araguaia and Brasília belts between the Amazon and São Francisco cratons), the Paraná intracratonic basin, the southern part of the São Francisco craton, and the Mantiqueira province (with the coastal Ribeira belt). Although the fast polarization directions vary across the region, consistent orientations are observed over hundreds of kilometers. The fast polarization directions tend to be close to the absolute plate motion given by the hot-spot reference model HS3-NUVEL1A. However, correlations with geological structures are also observed in the southern Brasilia belt and in the Ribeira belt, respectively located SW and S of the São Francisco craton. On the other hand, in the northern Tocantins province, the fast shear-wave direction (~N60°S) is oblique to the SW–NE trend of the geological units and faults, and no anisotropy contribution from lithospheric sources can be clearly identified. Overall, the fast polarization directions show a fan-shaped pattern strongly suggesting asthenosperic flow around a thick and stiff keel in the southern part of the São Francisco craton, consistent with the high-velocity anomaly revealed by recent surface-wave tomography. The observed NW–SE directions in the southern part of the Brasília belt may also be interpreted as resulting from asthenospheric flow channeled between the São Francisco craton and a cratonic block beneath the Paraná basin. The largest splitting delays observed in the southern Brasília belt and in the Ribeira belt (up to 2.4 s) suggest contributions from both lithospheric and asthenospheric sources in those two areas. Our preferred model for the anisotropy causing the observed pattern of SKS splitting consists of flow-induced deformation in the asthenosphere caused by the absolute plate motion (roughly towards W or WSW) with flow channeled around a thick cratonic keel. In the southern Brasília and in the Ribeira fold belts, the large delays and the parallelism with geological structures indicate additional anisotropy contribution from lithospheric sources.

Keywords: anisotropy; SKS splitting; upper mantle; plate motion; asthenosphere

1. Introduction

The study of seismic anisotropy yields information on the strain-induced fabric within the Earth and allows an

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understanding of the deformation or the structure of the mantle, in a way that cannot be achieved by other geophysical techniques. Anisotropy can be observed in the crust [e.g., 1,2], the upper mantle [e.g., 3–5], the transition zone [e.g., 6,7], the upper section of the lower mantle [8], and the D″ layer [9]. A shear wave propagating through an anisotropic medium is split into a fast and a slow shear waves polarized in mutually perpendicular directions, which can be recorded at a seismic station. Seismological and petrophysical studies [e.g., 4] suggest that the main source of anisotropy that causes splitting of teleseismic S waves is located within the first 400 km of the upper mantle and is related to the crystal preferred orientation (CPO) of olivine, the most abundant and deformable mineral in the upper mantle.

The development of olivine CPO in the upper mantle may result from past and present deformation. Past tectonic deformation processes are expected to imprint the lithospheric upper mantle with a crystallographic fabric which can remain stable after thermal relaxation, hereinafter referred to as "frozen anisotropy" [e.g., 4,10–12,72]. Olivine CPO also develops in association with present deformation and flow of the asthenospheric mantle that accommodates or causes plate motion, which is the main cause of upper mantle anisotropy beneath oceanic basins [13–15].

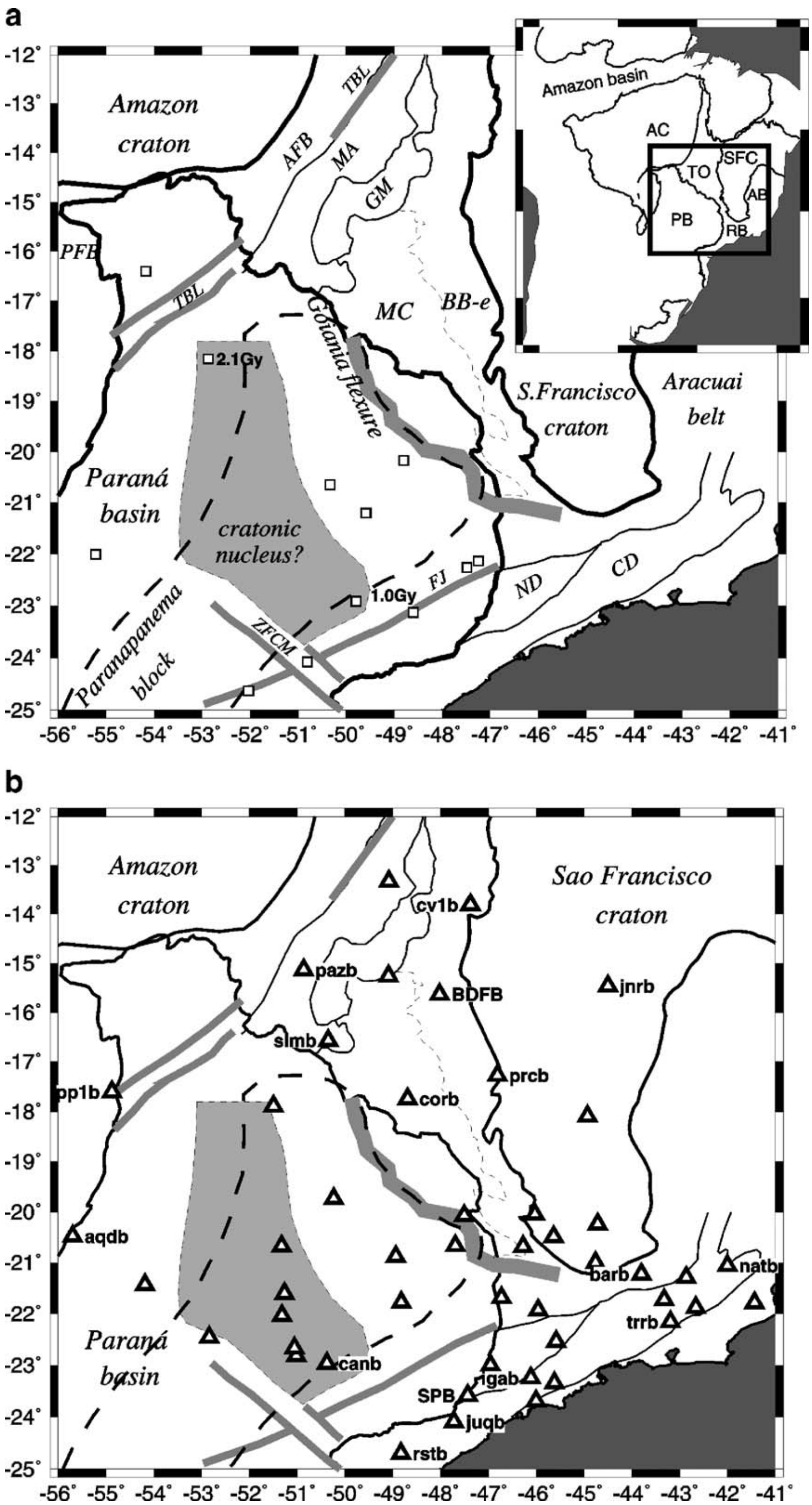
In continental areas, Vinnik et al. [16] attributed most of the observed anisotropy as being caused by flow in the asthenosphere due to the absolute plate motion. On the other hand, Silver and Chan [17] and Silver [3] argued that the measured fast polarization directions correlate better with the orientation of the tectonic structures resulting from past or on-going deformation of the lithosphere than with the absolute plate motion [e.g., 18]. Savage [4] reviewed the debate regarding the dominant cause of the anisotropy in stable continental areas, lithospheric (frozen) versus asthenospheric (plate motion), and recognized that no single hypothesis can easily explain all observations, and both lithospheric and asthenospheric anisotropy can contribute to the observed shear-wave splitting beneath continents, with asthenospheric flow perhaps being channelled along topography at the base of the lithosphere [e.g., 19–22]. A more recent review of anisotropy beneath continents is given by Fouch and Rondenay [23].

Few seismic anisotropy measurements have still been made in South America, east of the Andes, and lithospheric as well as asthenospheric sources have been invoked. James and Assumpção [24] showed that the fast polarization direction in SE Brazil varies according to the structural trend and favoured frozen anisotropy in the lithosphere as the main mechanism to cause SKS splitting. On the other hand, Helffrich et al. [25] analysed a few stations in southern South America and concluded that upper mantle anisotropy was due mainly to the present absolute plate motion. Detailed analysis of SKS splitting in the transcurrent Ribeira belt (SE Brazilian coast, Fig. 1) by Heintz et al. [26] suggests that both lithospheric and asthenospheric fabrics may contribute.

The study of shear wave splitting is therefore a useful tool to investigate deformation processes in the mantle and may be used to assess different models of orogeny or continental rifting for instance [e.g., 27–29]. It may also provide clues on the present plate dynamics as well as on the mechanical coupling between the crust and the underlying mantle during the deformation history of the continental lithosphere.

Seismic anisotropy below a seismological station can be inferred through the study of core-refracted shear waves such as SK(K)S and PK(K)S. These waves propagate in the outer core as P waves and undergo a P-to-S conversion at the core mantle boundary (CMB) on their way up to the surface, arriving at the station at nearly vertical incidence. Because of the P-to-S conversion at the CMB, these phases are initially polarized along the radial direction. Quite often, however, SK(K)S/PK(K)S waves exhibit energy on the transverse component, which is best explained as the result of shear-wave splitting due to propagation within an anisotropic medium. Transverse energy could also be caused by scattering and out-of-plane refraction from dipping interfaces. Assuming these effects are not important (which can be checked by analysing events from different backazimuths), anisotropy is the best explanation for the transverse energy. The anisotropy measured through SK(K)S or PK(K)S phases represents a vertically integrated effect of anisotropy from the CMB to the surface.

Two parameters are measured at the station: (1) ϕ, the polarization direction of the fast S-wave, regarded as a reliable proxy for the orientation of the [100] axis of olivine in the upper mantle, and (2) dt, the delay between the arrival time of the fast and slow split waves. dt is proportional to the thickness and the intrinsic anisotropy of the anisotropic layer; it depends on both the orientation of the ray path of the incoming S-wave with respect to the elastic matrix of the anisotropic medium, and the vertical coherence of the mantle fabric. The average delay time measured in continental areas is $\sim$1 s [3], although delays $>$2 s have been measured above large strike-slip fault systems (e.g., station IGAB in Brazil, on the Ribeira transcurrent fault system [26]; and station BUDO in Tibet, in the vicinity of the Kunlun fault [30]).


a
Amazon craton
TBL
AFB
MA
GM
MC
BB-e
PFB
Goiania flexure
2.1Gy
S.Francisco craton
Aracuai belt
Paraná basin
cratonic nucleus?
Paranapanema block
ZFCM
FJ
1.0Gy
ND
CD
Amazon basin
AC
TO
SFC
AB
PB
RB
b
Amazon craton
Sao Francisco craton
cv1b
pazb
BDFB
jnrb
slmb
pp1b
prcb
corb
aqdb
barb
natb
trrb
canb
rigab
SPB
juqb
rstb
Paraná basin
-12°
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This study presents splitting measurements on core refracted shear waves recorded in central and southeast Brazil. Data have been collected at 46 sites equipped with portable broadband seismic recorders, in addition to two permanent stations (BDFB and SPB, Fig. 1b). The purpose of the study is to investigate the potential mechanical coupling between the crust and the upper mantle in a structurally complex region encompassing a wide variety of geological structures such as cratonic root, orogenic belts, basaltic trapps and sedimentary basins.

2. Geological setting

The geological evolution of central and southeast Brazil spans from the Archaean to the Cenozoic and involves a large variety of structural units (Fig. 1a). In southeast Brazil, the São Francisco craton, Archaean to Mesoproterozoic in age (3.3–1.5 Ga), is surrounded by slightly diachronic mobile belts. The Tocantins Province (Fig. 1a), between the São Francisco and Amazon cratons, is a Neoproterozoic orogen with three domains: the Paraguay belt (at the southern margin of the Amazon craton), the Araguaia belt (at the eastern margin of the Amazon craton) and the Brasília belt developed at the margin of the São Francisco Craton. Four main geological units form the Brasília belt: a SSW–NNE trending Neoproterozoic Magmatic Arc (MA in Fig. 1a), formed off the coast of the São Francisco micro-continent, operating from 890 Ma ago until final ocean closure and continent collision at ca. 630–600 Ma [31]; the Goiás Massif (GM), an assembly of Paleoproterozoic rocks (~2 Ga) and Archean terrains (2.5–2.9 Ga), accreted to the São Francisco "plate" at 790–750 Ma; a Metamorphic Core (MC) with high-grade metamorphic complexes and thrust faults; and an "external zone" (BB-e) with low grade metasediments of passive margin sequences. The southern part of the Brasilia belt, with roughly NW–SE trending structures, results from the convergence at ca. 790 Ma, between the São Francisco craton and the Paranapanema block (Fig. 1a), presently underneath the Paraná basin [32,33].

East of the São Francisco craton stretches the Ribeira–Araçuaí belt, trending NS to NE–SW. Together with its African counterpart, the West Congo orogen, the Ribeira–Araçuaí belt formed during the final amalgamation of western Gondwana (580–540 Myr) and later split during the opening of the South Atlantic Ocean (130 Ma). At ~21°S, the Ribeira–Araçuaí belt displays a change in structural trend and in tectonic style: the southern, ENE-trending part of the belt is dominated by lithospheric-scale, dextral transcurrent faults (especially the Central Domain, CD in Fig. 1a), whereas in the northern, NS-trending part thrusting towards the craton predominates.

To the southwest, the Brasilia and Ribeira–Araçuaí belts are buried under the Paraná basin, one of the worldwide largest igneous province, thought to result from the upwelling of the Tristan da Cunha plume at ca. 135 Ma. Continental scale [34–37] and more detailed regional seismic tomographies [38,39] show high velocity anomalies extending down to 200 km depth under the Paraná basin, roughly consistent with a postulated cratonic nucleus [32,40] inside a larger Paranapanema block [33]. The suture between the São Francisco craton and the Paranapanema block is marked by a strong gradient of Bouguer anomalies [41; Fig. 1]. VanDecar et al. [42] and Schimmel et al. [38] revealed the existence of a cylindrical shaped low velocity anomaly located underneath the NE part of the Paraná basin and extending from 200 to 600 km depth. This anomaly has been interpreted as the fossil conduit of the Tristan da Cunha plume, although its thermal origin is still debated [43].

In the north of the Paraná basin and in the Tocantins Province, geological and aeromagnetic data [44] reveal a major NE–SW trending lineament. This structure, known as the Transbrasiliano Lineament (TBL), extends from the NE coast of Brazil to Paraguay, passing close to the border between the Araguaia belt and the Magmatic Arc (Fig. 1a). The TBL is thought to represent a major Neoproterozoic suture between two continental plates: one in the SE (containing the São Francisco craton and

Fig. 1. (a) Main geological provinces in Central and SE Brazil. Inset: limits of the Amazon craton (AC), São Francisco craton (SFC), and the Paraná basin (PB); TO = Tocantins Province, RB = Ribeira Belt, AB = Araçuaí belt. Main map: the Tocantins Province is comprised of the Araguaia foldbelt (AFB) and several units of the Brasília belt: MA = Neoproterozoic Magmatic Arc, GM = Goiás Massif, MC = Metamorphic Core of the internal zone, BB-e = external zone of the Brasília belt. The shaded area in the middle of the Paraná basin is an inferred cratonic nucleus [32,40] where radiometric dating of two basement samples indicates Proterozoic ages of 1.0 and 2.1 Ga; other squares indicate basement dates of Brasiliano–PanAfrican age. The gray lines in the Paraná basin are inferred fault zones [40]: FJ = Jacutinga Fault; TBL = TransBrasiliano Lineament; ZFCM = Curitiba–Maringá Fault Zone. The dashed line is the limit of the Paranapanema block [33]. The thick shaded line ("Goiânia flexure") indicates the strong gravity gradient marking the Neoproterozoic suture between the São Francisco craton and the cratonic block beneath the Paraná basin. In the Ribeira belt, ND = Nappe Domain; CD = Central Domain [73]. (b) Station locations (triangles). Only stations mentioned in the text are labelled. Main geological units and provinces as in (a).

the Paranapanema block) and the other in the NW (containing the Amazon craton). This lineament extends into Africa along the Kandi lineament [45]. It played a predominant role in shaping the Gondwana geology and has been reactivated after the Gondwana assembly with transtensional tectonics.

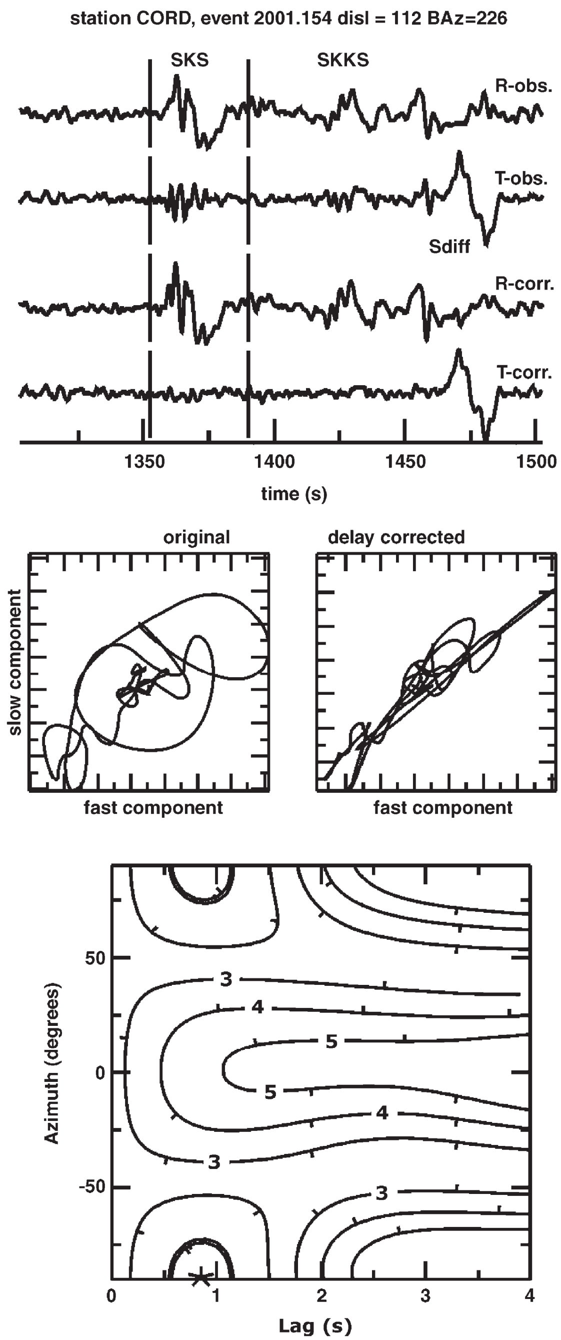

Fig. 2. Example of SKS splitting for station *corb* in the Tocantins province. Top diagram: first two traces are the original radial and transverse records showing a large signal on the transverse component; bottom two traces are the anisotropy corrected signals; the two vertical lines show the time window used in the SKS analysis. Middle diagrams show the original and corrected particle motions. Bottom diagram: energy contour of the transverse component as a function of the delay ("lag") and the fast anisotropy azimuth; the star indicates the values that best eliminate the signal in the transverse component; the thick contour line indicates the 95% confidence region. Note that the correction calculated for the SKS phase also reduces the transverse component of the SKKS phase.

3. Data processing

Shear wave splitting measurements were performed using Silver and Chan's [17] algorithm: the fast polarization azimuth (ϕ) and the lag time between fast and slow components (dt) are determined through a grid search by correcting the observed components from the anisotropy effect so as to minimize the energy on the transverse component. The energy on the transverse component is evaluated for a wide range of ϕ and dt (increments of 1° and 0.05 s, respectively) to retrieve the values that best remove the anisotropy (Figs. 2 and 3). The uncertainties in each splitting measurement are based on the sharpness of the minimum in the energy contour and the degrees of freedom in the data window [17]. This method assumes anisotropy to be located in a single horizontal layer. The influence of filters and time windows used in the splitting analysis has been systematically checked, and only data showing no variations with respect to small changes in the window size are considered reliable. Data were preferably not filtered, but when required, we used a band pass filter with corner frequencies mainly at 0.03 and 0.3 Hz.

To increase the reliability of the dataset and remove subjectivity in manual window picking, the more recently acquired data have been processed using the automated method of Teanby et al. [46]: a measurement window is manually picked and an increment is defined to automatically vary its start and end time. The Silver and Chan's algorithm is performed for each window thus defined. A cluster analysis is then used to identify stable regions. Two criteria based on the variance of clusters and measurements are used to determine the optimum cluster, and from this cluster, the analysis window with the smallest errors on ϕ and dt is selected. Fig. 4 shows an example of the automated processing for station *pazb*. Comparisons with earlier measurements (with the best window chosen by the operator)

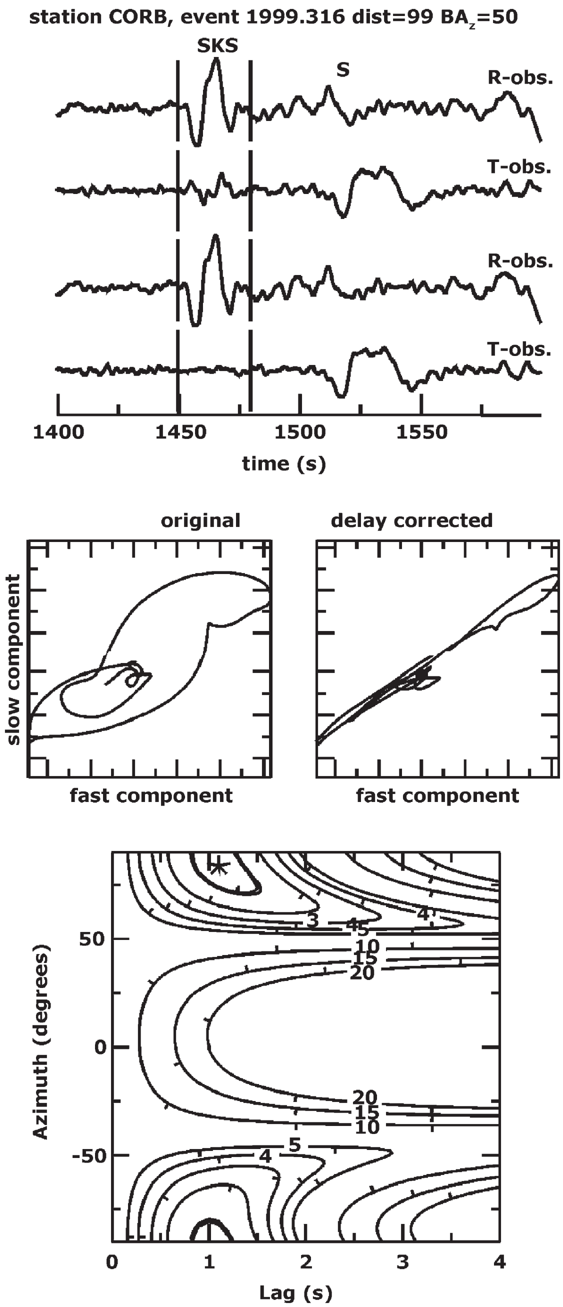

Fig. 3. Example of SKS analysis for station *canb* in the Paraná basin. Diagrams as in Fig. 2.

showed similar results and re-processing of the old data was not necessary.

4. Results

Individual results have been sorted into two categories, 'good' and 'fair'. 'Good' results exhibit small errors (<15° and <0.5 s for ϕ and dt, respectively) and satisfy four criteria [20]: good signal-to-noise ratio and no interference with other phases; ellipticity of the particle motion in the horizontal plane; its linearization after anisotropy removal; and waveform coherency between the fast and slow shear waves. Results satisfying three criteria are classified as 'fair', and those satisfying only two or less criteria are discarded.

Two examples of 'good' measurements are shown in Figs. 2 and 3 for stations *corb* and *canb*, located in the central part of the Brasilia belt and in the Paraná basin, respectively. In Fig. 2 anisotropy affects both SKS and SKKS waves. The best anisotropy parameters retrieved from the SKS phase ($\phi=-89°\pm8°$ and dt=0.85±0.15 s) also remove the energy on the transverse component associated with the SKKS phase. The splitting measurement performed on the SKKS phase indeed gives $\phi=-84°\pm5°$ and dt=1.15±0.12 s. In most cases, the anisotropy parameters determined from SKS and SKKS are consistent. If not, the hypothesis of a horizontal layer of anisotropy might not be sufficient to explain the observations, and more complex media, such as 2-layer systems, inclined axis of symmetry, lateral heterogeneities, or even contribution from the D″ layer have to be envisioned. In Fig. 3, the SKS wave arrives at station *canb* from the Southwest, i.e., at 45° from the E–W direction of the measured fast polarization (89°±4°), which is the most favourable geometry for the detection of SKS splitting.

Fig. 5 shows all measurements carried out at three stations (*BDFB*, *corb*, and *canb*) with respect to the backazimuth of the events. If the initial polarization of the incoming wave is parallel or orthogonal to the fast anisotropic direction, or if there is no apparent anisotropy beneath the station, this will result in a lack of energy on the transverse component. Those measurements define a particular class of results known as 'nulls'. Null measurements therefore arise when the event backazimuth is parallel to the fast or slow polarization direction (e.g., Fig. 5a and b for stations *BDFB* and *corb*). Null measurements could also originate from complexity in the anisotropy, such as several layers or dipping layers; however, no clear null (i.e., SKS with large signal to noise ratio) has been observed more than 20° away from the presumed fast or slow direction, for stations listed in Table 1.

Fig. 5 also shows that the fast polarization direction measured at the station does not vary with the backazimuth of the event. The average direction for a station was then taken as the mean direction of all measurements. Statistics for directional data [47] were used to get the mean direction and its 95% confidence limits (Table 1).

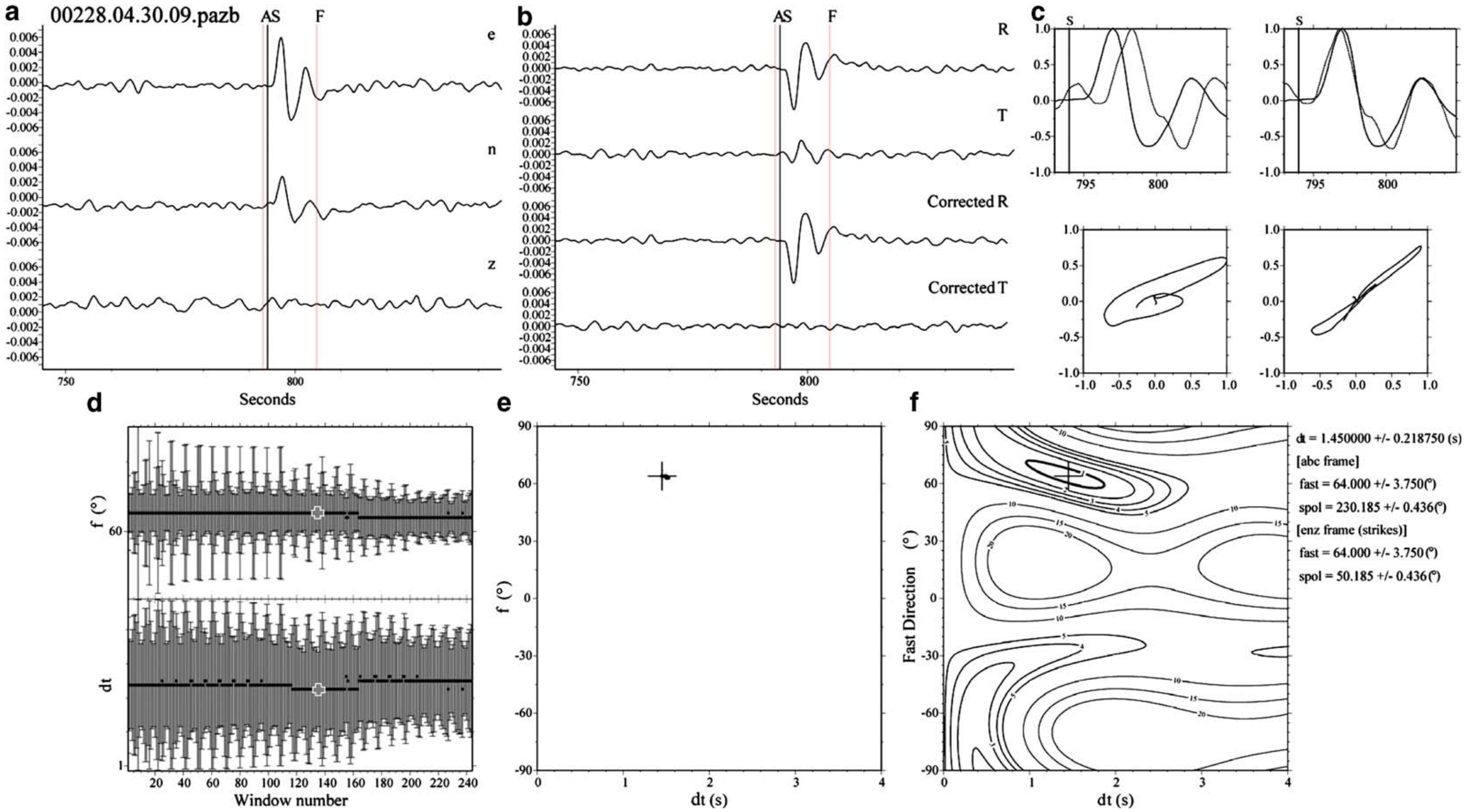

Fig. 4. Example of shear wave splitting measurement, at station *pazb* in the Tocantins Province near the TBL, using the automated code of Teanby et al. [46]. From top left to bottom right: a. Raw data in the geographical referential. S is the S-wave pick, A and F are the beginning and end time of the measurement window, manually picked. b. Radial and transverse components before and after rotation of the traces and time shifting. After correction of the anisotropy, note the removal of energy on the transverse component. c. Waveform coherency and particle motion before (left) and after (right) removal of the anisotropy effect. Before correction, the two waveforms are similar but shifted by dt, and the particle motion is elliptical. After correction, the two waveforms become perfectly aligned, and the particle motion is linearized. d. Representation of the ϕ and dt values obtained from 250 analysis windows. Stable solutions correspond to plateau associated with small error bars. The gray cross indicates the solution that was chosen from the cluster analysis. e. Plot of ϕ vs. dt for the 250 measurement windows. The plateau in figure d is condensed in a tight cluster of points in figure (e). A cluster analysis is performed and results in triangle marking the cluster position and a cross marking the optimum cluster, associated with the lowest variance. f. Energy contour in the ϕ vs. dt diagram. The thick contour indicates the 95% confidence interval and the cross shows the solution.

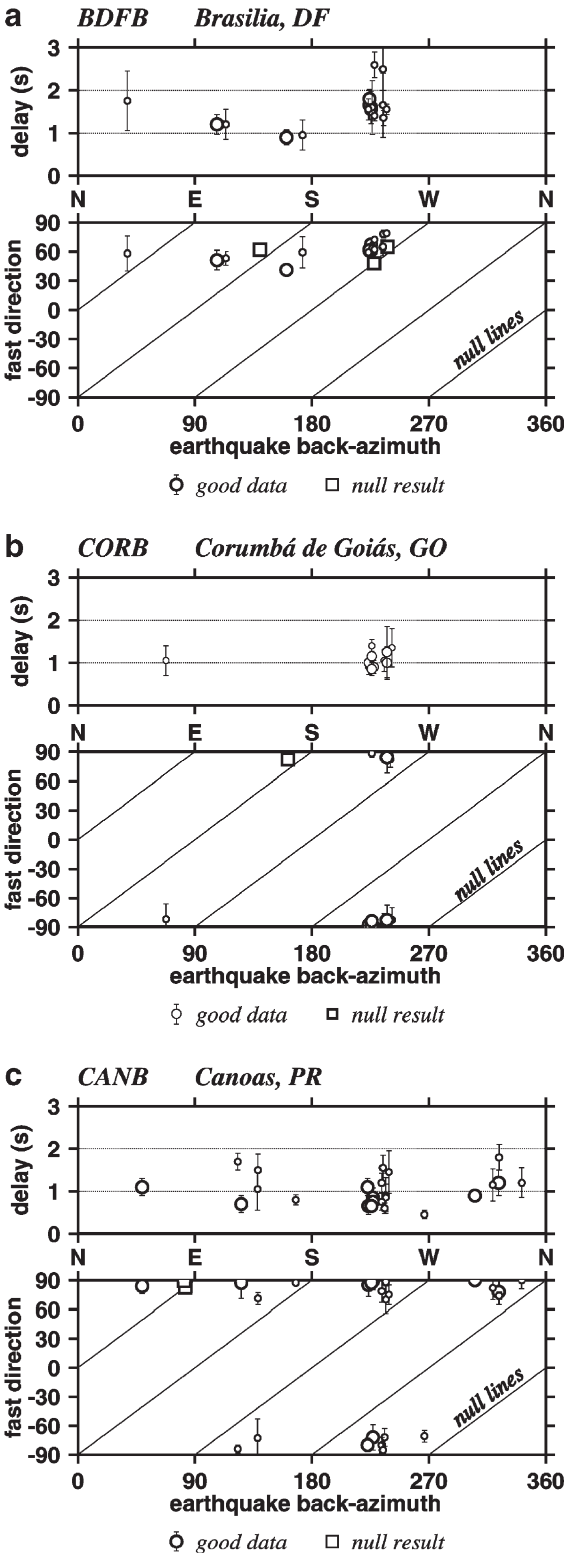

Fig. 5. Measurements of time delay dt (top plot) and fast directions ϕ (bottom plot) with respect to the earthquake backazimuth. Large and small circles indicate good and fair measurements. The inclined lines in the bottom diagram indicate locii of backazimuth parallel to the fast or slow direction; near these lines one should expect null results which are indicated by the square. (a) permanent GTSN station BDFB, (b) station *corb*, (c) station *canb*.

The estimated error in each individual measurement was used as weight. In addition, half weight was used for fair data compared with good quality data. Most stations had a well defined fast polarization direction. In some cases (*aqdb*, *slmb*, *jnrb*) no statistically significant average direction could be defined, either because the measurements had poor quality, the scatter in the individual directions was too large, or the number of data was too limited. The average time delay at a station was computed as the mean of all individual measurements, weighted by the uncertainty and quality of each data.

For example, a total of 17 SKS and SKKS phases at the permanent station *BDFB* (Fig. 5a) gave an average orientation of the fast S-wave polarization of 63°±4°, with a standard deviation of 8°, and an average delay of 1.5±0.2 s. An early determination by Vinnik et al. [16], based on a single event for the nearby station BDF, had given ϕ=40° and dt=1.2 s, whereas Russo and Silver's [48] measurements were ϕ=53°±15° and dt=1.5±1.0 using only three events. These large differences (23° or 10°) show that one must be careful when interpreting results based on only a few events. More recent measurements with 51 events at station *BDFB* by Ivan et al. [49] gave ϕ=62°±3° and dt=1.1±0.1 s, in good agreement with our results, specially for the fast polarization direction.

Table 1 shows the S-wave splitting results from stations in central and SE Brazil, not analysed before by James and Assumpção [24] or Heintz et al. [26]. The measurements performed at stations in the Ribeira belt are described in more detail by Heintz et al. [26]. Fig. 6 displays the fast shear-wave polarization directions from Table 1 together with previous results of James and Assumpção [24] and Heintz et al. [26]; it also shows the structural trend in Central and SE Brazil marked by the main faults [50].

Although the fast polarization directions (ϕ) are not uniform in the whole study area, consistent patterns within ranges up to 500 km can be observed. In the Tocantins Province, from station *pp1b* to *cv1b*, ϕ is close to N60°E. Within the Paraná basin, above the cratonic nucleus, small splitting delays and EW fast S-wave polarizations were retrieved. In the southern Brasília belt and northeastern Paraná basin, ϕ trends NW–SE roughly parallel to the Goiânia suture. In the central part of the

Table 1
New SK(K)S splitting results for SE and Central Brazil. "ϕ" is the direction of the fast polarization and "dt" is the splitting delay time; uncertainties (dϕ and dd$t$) are 95% confidence limits. "N" is the number of measurements

Station code	Lat. (°)	Long. (°)	ϕ (°)	dϕ (°)	dt (s)	dd$t$	N	Station name, state
Ribeira belt								
barb	−21.222	−43.801	63	10	1.7	0.8	2	Barbacena, MG (SE+SW)
"			−73	10	1.0	0.5	2	"(NE+NW)
daeb	−23.6903	−46.0099	82	6	1.2	0.3	6	Bom Sucesso, MG
natb	−21.055	−42.004	87	7	0.7	0.2	4	Natividade, RJ (SW)
"			−61	10	1.1	0.3	1	" (North)
Paraná basin								
canb	−22.9681	−50.3778	88	4	0.9	0.1	18	Canoas, SP
nupb	−20.6628	−47.6859	79	5	1.1	0.4	15	Nuporanga, SP
pacb	−21.6074	−51.2618	95	11	0.8	0.2	8	Pacaembu, SP
popb	−22.4565	−52.8368	72	6	0.7	0.1	15	Porto Primavera, SP
São Francisco craton								
bamb	−20.0398	−46.0308	130	6	1.1	0.4	7	Bambuí, MG
trmb	−18.0922	−44.9290	103	18	0.8	0.3	8	Três Marias, MG
prcb	−17.2702	−46.8188	98	7	1.0	0.3	5	Paracatu, MG
Tocantins Province								
BDFB	−15.6418	−48.0148	63	4	1.4	0.2	17	Brasilia, DF (GTSN)
corb	−17.7433	−48.6892	92	3	1.0	0.1	8	Corumbá, GO
cv1b	−13.8142	−47.3767	75	6	1.4	0.3	11	Cavalcante, GO
gnsb	−15.2644	−49.0855	94	6	1.2	0.2	9	Goianésia, GO
jatb	−17.893	−51.493	107	15	1.0	0.3	11	Jataí, GO
pazb	−15.1369	−50.8634	67	3	1.6	0.3	11	Araguapaz, GO
porb	−13.3304	−49.0787	70	8	1.4	0.9	5	Porangatu, GO
pp1b	−17.6003	−54.8797	75	3	1.2	0.2	21	Ponte de Pedra, MS

Ribeira belt, ϕ is ENE oriented. Interestingly, the anisotropy of electrical resistivity determined by long-period magnetotelluric surveys [51] is generally consistent with the seismic anisotropy: observed directions of maximum conductivity are ENE across the Ribeira belt, and WNW in the southern Brasília belt, SW of the São Francisco craton.

Fig. 7 compares all measured ϕ with the absolute plate motion (APM) given by the HS3-NUVEL1A model [52]. The APM of the South American plate is not well known and different directions result from different models used to define the absolute reference frame. While for fast moving plates, different models tend to show little difference in orientation [e,g,53], for the relatively slow moving South American plate, different models predict directions up to 90° apart, as indicated in Fig. 6. The HS3-NUVEL1A model [52], one of the most used absolute reference frame, is strongly constrained by the hotspot migration rate in the Pacific. For this model, SE Brazil moves towards WSW (azimuth of 256°±12°). On the other hand, other models based on no-net-rotation of the lithosphere, either using geological data for the relative plate motion [52] or recent GPS measurements [54,55], give an absolute motion for SE Brazil close to NNW. Wang and Wang [56] presented a third APM model whereby only the hotspot trends were used (no migration rates were used), allowing hotspots to move slightly along the track. This model predicts a NW motion for SE Brazil.

Although large scatter is observed in Fig. 7, the peak of the distribution is close to that predicted by HS3-NUVEL1A model. Given the wide distribution of our stations across different tectonic provinces, this coincidence seems to indicate that an asthenospheric contribution to the observed anisotropy is very likely and that the absolute motion of the South American plate is probably close to that predicted by the HS3-NUVEL1A model.

5. Discussion

5.1. Ribeira belt

In the Ribeira belt, the fast shear waves display polarization directions close to the WSW–ENE trend of

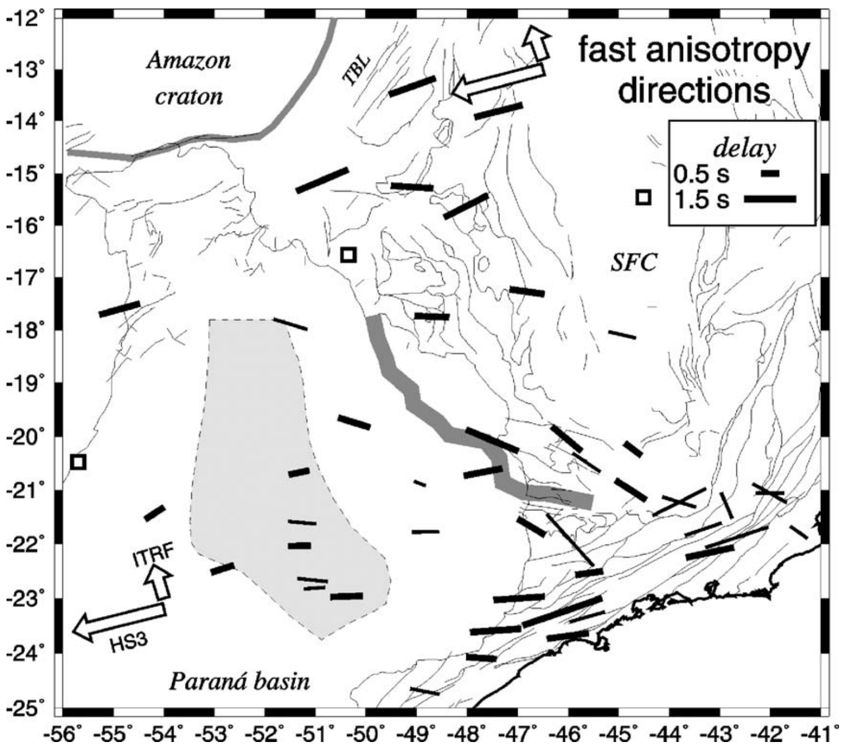

Fig. 6. Fast polarization directions in SE and Central Brazil. Thick and thin bars indicate good and fair average direction for each station (Table 1). Squares indicate stations for which no reliable average fast direction could be determined. Thin lines show the main geological faults [50]. The two arrows indicate the absolute plate motion according to the fixed hot-spot model HS3-NUVEL1A [52] with 48 mm/y, and the GPS/ITRF model [55] with 12 mm/y.

the fold belt, especially in its central part, where transcurrent shear zones predominate. The shear zones were due to escape tectonics during the Brasiliano/Neoproterozoic convergence between the cold and thick Congo and São Francisco cratons [57]. Interestingly, the

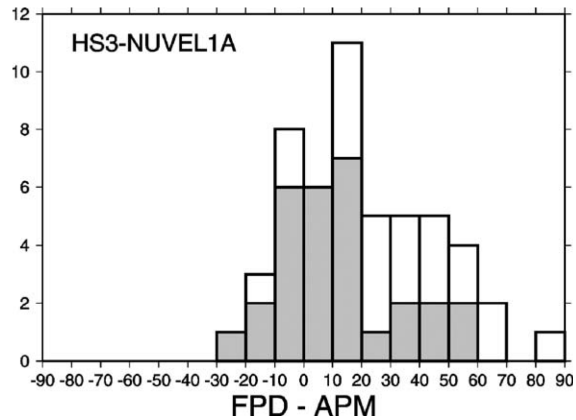

Fig. 7. Comparison of the fast polarization direction (FPD = ϕ) with the absolute plate direction (APM, HS3-NUVEL1A [52]). Gray and open bars indicate good and fair data, respectively.

WSW–ENE direction of the anisotropy measured along the Ribeira belt, parallel to the Brasiliano structural trend of the belt, does not seem to have been much affected by the extensional deformation during the Mesozoic Atlantic rifting. This is in good agreement with the model of transtensional rifting due to inherited mechanical anisotropy suggested by Tommasi and Vauchez [58]. An abrupt change in polarization direction occurs at the boundary between the Ribeira and the southern Brasilia belts, suggesting some contribution from lithospheric sources. However, at some sites in the Ribeira belt, the delay between the fast and slow split waves is very large (up to 2.4 s at station IGAB). This represents one of the largest delays observed worldwide and requires a thick anisotropic layer. Heintz et al. [26] show this large delay time to be a reliable measurement. To be explained as resulting from a single lithospheric anisotropic layer, large delay times (> 1.5 s) require either an unusually large apparent anisotropy (> 5%) or a thick lithosphere (> 150–200 km), or the contribution of oriented melt pocket [e.g., 29]. For an orogenic lithosphere of normal thickness, even assuming that the lithospheric fabric is of the transcurrent-type (vertical foliation bearing an horizontal lineation [e.g., 59], the expected delay time is < 1.5 s. A possible scenario to explain large delay time is a contribution to anisotropy from both the lithosphere and the asthenosphere. These contributions may combine positively and result in large delay times only if the anisotropies in the two layers are almost parallel. This condition is fulfilled beneath active faults such as the Altyn Tagh in Tibet [30,59]. For ancient orogenic domain, an addition of the lithospheric and asthenospheric contributions requires that the asthenospheric flow due to plate motion is close to the orogenic fabric, such as observed in some areas of eastern North America [21]. Considering that the HS3-NUVEL1A APM is close to the structural trend of the Ribeira belt, Heintz et al. [26] proposed that the frozen fabric in the lithosphere and the APM related fabric in the asthenosphere are close enough to mimic a single layer.

In the northern part of the Ribeira belt, the anisotropy pattern is more complex, which is probably related to the transition between a transcurrent fabric due to strike-slip faults (~vertical flow plane and sub-horizontal flow direction) in the southern domain to a flat contractional fabric (eastward gently dipping flow plane and flow direction) in the northern domain where NS-trending thrusts and nappes predominate [57,60]. In the transition zone, measurements performed at stations *natb* and *barb*, (Fig. 1b) suggest different polarization directions for fast SK(K)S waves arriving either from the south or from the north (Table 1). The available data is not enough to distinguish between several possible explanations such as 2-layer system, inclined axis of symmetry, or lateral variation. Recent measurements of the anisotropy of magnetic susceptibility in this domain [60], highlighted a progressive transition from transcurrent-dominated to thrust-dominated deformation regimes, and thus from a fabric characterized by a vertical foliation bearing a sub-horizontal lineation to an eastward gently dipping foliation bearing a down-the-dip plunging lineation. Therefore, depending on their backazimuth, the incoming waves may preferentially sample one type of fabric, which would be consistent with the observations in Table 1 (stations *barb* and *natb*).

5.2. Paraná basin

In the Paraná basin, at least two groups of fast polarization directions are present. In the NE part, the fast polarization direction tends to be NW–SE oriented, parallel to the structural grain of the metamorphic core of the Brasilia belt and consistent with its presence beneath the edge of the sedimentary basin. In the central part of the basin, where a possible cratonic nucleus has been proposed [32,33,40,61] the anisotropy is small (delays less than 1.0 s) but consistently EW oriented. This may indicate a different origin for the deformation induced anisotropy beneath the central part of the basin.

In the central part of the Paraná basin, if the anisotropy is lithospheric in origin, two possibilities should be considered to interpret the EW fast directions: (a) deformation associated with pre-Brasiliano orogens inherited with the cratonic Paranapanema block, or (b) deformation associated with the evolution/subsidence of the Paraná basin. Quintas et al. [62] analysed subsidence rates in the central part of the Paraná basin and estimated small crustal stretching factors (beta < 1.5) during the basin evolution. The domain that underwent maximum stretching for the two main events in the Palaeozoic (at 440 Ma and 296 Ma) trends roughly N–S and might suggest that extension was mainly E–W oriented, assuming extension was orthogonal to the rift (which is an oversimplification, see for instance [57]). If the observed anisotropy was related to the E–W extension, a uniform lithospheric deformation outside the rift zone would be required, such as envisaged in the Mckenzie [63] model or the Vertically Coherent Deformation (VCD) model of Silver [3]. However, anisotropy studies of present day continental rifts [29,64,65] show that the fast S-wave direction tends to be rift parallel in the active central zone; outside the rift zone no rift-perpendicular fast direction has been consistently observed and the uniform stretching models of McKenzie [63] and Silver [3] do not seem to be supported. Outside the rift zones, seismic anisotropy seems to be strongly influenced by inherited fabric, such as in the Rhine graben [66] or the East-African Rift [65,74]. Given that the history of extension in the Paraná basin is poorly understood, SKS splitting data cannot easily be correlated with past lithospheric deformation.

Alternatively, if the anisotropy lies below the lithosphere, it could be related to the present-day APM which would be close to the WSW direction predicted by the fixed hotspot model HS3-NUVEL1A. So, at least two hypotheses could explain the anisotropy beneath the central Paraná basin: (a) frozen lithospheric anisotropy (difficult to test because of the sedimentary cover and poorly known basin evolution), and (b) asthenospheric deformation from present E–W oriented APM, close to the HS3 model.

5.3. Tocantins Province

In the southern part of the Brasília fold belt, SW of the São Francisco craton, the fast split waves are polarized NW–SE, parallel to the Goiânia flexure (Fig.

1a) and the general structural trend of the belt. This area is also characterized by prominent aeromagnetic anomalies oriented NW–SE. The observed lithospheric fabric is consistent with a collision between the Paranapanema cratonic block beneath the Paraná basin and the São Francisco craton. The polarization of the fast split S-waves parallel to the orogenic grain is thus consistent with a lithospheric origin, as previously shown by James and Assumpção [24] and Heintz et al. [26]. It might however be explained also by a deflection of the APM-driven asthenospheric flow around the southern tip of the craton. Considering the rather large delay times retrieved in this domain and the parallelism of the orogenic grain with the expected deflected asthenospheric flow, a combination of an asthenospheric and lithospheric anisotropy is also possible.

In the northern Tocantins province the measurements indicate a fast polarization direction roughly WSW–ENE, significantly oblique with respect to the main geological units (Fig. 1a) and the Transbrasiliano Lineament (Fig. 6). The lack of parallelism between ϕ and the TBL may indicate that the dextral transcurrent motion observed along the TBL did not affect a large volume of subcontinental mantle. If the observed fast polarization (ENE) was caused by a lithospheric anisotropy associated to the SW–NE trending TBL, then an ENE lineation (flow) and SE-dipping lithospheric foliation would be required. No record of such fabric is known in the geological evolution of the Tocantins province [e.g., 31]. Therefore, the observed anisotropy is probably not directly related to the TBL or other past tectonic processes, but rather to an asthenospheric source. The ENE asthenospheric flow could be parallel to the absolute plate motion (if the HS3-NUVEL1A model is assumed) or could denote a deflection around the southern tip of the São Francisco craton from a roughly E–W absolute motion.

In the central Brasília belt, a well defined E–W fast polarization direction is observed at stations *corb* and *prcb*, oblique and perpendicular to the structural trend, respectively. If the cause of the splitting was frozen anisotropy, then mantle fabric due to lithospheric scale thrusting towards the craton would be required. The western border of the São Francisco craton is gradational and the surface limits depicted in Figs. 1 and 6 do not involve deep lithospheric discontinuities. In fact, westward extension of the cratonic crust beneath the external and internal zones of the Brasília belt (called “Franciscan plate”) has been suggested from geological arguments [e.g., 67] and seismic properties of the crust beneath the belt [68]. This makes a lithospheric scale thrusting beneath the external zone of the Brasília belt rather unlikely. Alternatively, the E–W S-wave polarization (ϕ) might be caused by APM-related flow in the asthenosphere.

5.4. Fan-shaped pattern and deflected asthenospheric flow

A lithospheric contribution to the anisotropy is likely in the central Ribeira belt and in the southern Brasilia belt where delay times are large and the polarization of the fast S-wave is well correlated with the orogenic fabric at the regional scale. However, near E–W fast S-wave polarizations are observed over a large area in the central part of the Brasília belt and São Francisco Craton as well as in the southernmost Ribeira belt (stations *juqb* and *rstb*) and the central Paraná basin (Fig. 6). No single lithospheric source may account for the whole dataset since these domains have undergone contrasted geodynamical evolution. Even considering each domain separately does not allow to explain satisfactorily the observed EW polarization in terms of frozen lithospheric structure (as deduced from surface geology and geophysical studies). On the other hand, the EW polarizations together with the ENE polarizations further North in the Tocantins province and the NW–SE polarizations observed in the southern part of the Brasília belt, form a fan-shaped pattern open toward the São Francisco craton. This fan-shaped pattern of ϕ is rather consistent with what would be expected from a fabric caused by asthenospheric flow around and below the São Francisco Craton. In this interpretation, the present plate motion would be towards the W, close to the HS3-NUVEL1A model.

Fig. 8 shows the S-wave velocity anomalies obtained from a continental-scale Rayleigh-wave tomography by Feng et al. [36] using a joint inversion of waveforms and group velocities. The seismic velocity model at 150 km depth (Fig. 8a) suggests that the São Francisco Craton lithospheric thickness is larger in the southern part than in the central and northern parts. The fast polarization directions tend to wrap around the cratonic root strongly suggesting asthenospheric flow around the craton’s keel. The anomalies around 250 km depth (Fig. 8b) show a NW–SE low-velocity channel between the craton and the high velocity lithospheric block beneath the Paraná basin. The parallelism between ϕ and this low-velocity channel strongly suggests an asthenospheric flow controlled by lithosphere/asthenosphere boundary topography.

Because of the unconstrained depth of the anisotropy causing the SKS splitting in central and SE Brazil,

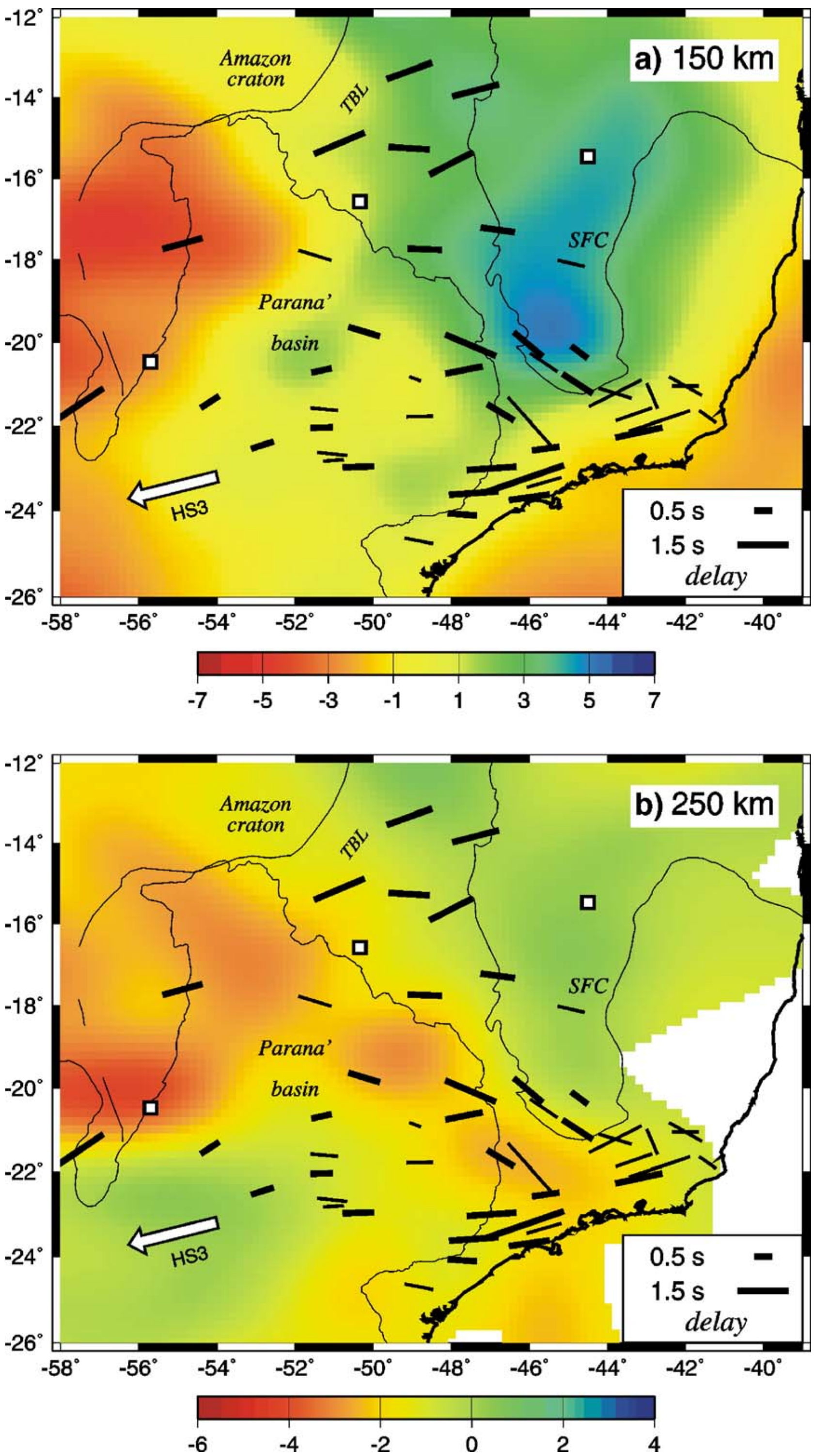

Fig. 8. Fast polarization directions from shear-wave splitting (black bars, thickness as in Fig. 6) and S-wave velocity anomalies from surface-wave tomography of Feng et al.[36]. Colour scale is % anomaly with respect to the IASP91 model. Open arrow indicates absolute plate motion according to the HS3-NUVEL1A model [52]. (a) anomalies at 150 km depth. Note the thicker lithospheric root of the southern part of the São Francisco craton. The fast polarization directions display a fan-shaped pattern suggesting a deflection around the craton keel. (b) Velocity anomalies at 250 km depth. Note the low-velocity "channel" between the São Francisco craton and a high-velocity block beneath the Paraná basin suggesting flow-induced anisotropy related to lithosphere/asthenosphere topography.

different hypotheses can be proposed to explain our observations, as discussed in previous sections. For example, if the absolute plate motion is WSW as in the HS3 model, simple asthenospheric flow could explain the WSW–ENE fast directions (in northern Tocantins and the Ribeira belt) and frozen lithospheric anisotropy could explain all other regions, despite lack of correlation with surface geology for the E–W directions in the central Brasília belt and southernmost Ribeira belt. Our preferred model to explain the observed patterns of SKS splitting consists of a main contribution from APM-related asthenospheric flow deflected by the São Francisco keel. Additional lithospheric anisotropy is also evidenced in two areas: the southern Brasília belt and in the central part of the Ribeira belt. In these two areas the large splitting delays and the correlation between ϕ and geological trends support a contribution from lithospheric frozen anisotropy formed during the Brasiliano orogeny. Since the Brasiliano fabric and the APM are rather close, a contribution of both sources is possible [26].

If the absolute plate motion is WSW, as given by the HS3 model, deflection would mainly affect the NW–SE oriented region in front of the São Francisco keel (Fig. 8a). In this case the E–W directions in the central Paraná basin and in central São Francisco craton could be interpreted as intermediate directions of the regional fan-shaped pattern. This would be consistent with the numerical modeling of Fouch et al. [21] which shows that a deep keel can affect the asthenospheric flow (and the resulting fast polarization direction) several hundred kilometers from its edge. Alternatively, the EW-fast polarizations could be related to a westwards absolute plate motion (still within the 95% confidence limit of the HS3-NUVEL1A model; [52]) with all other directions related to deflected flow (combined with frozen lithospheric anisotropy). This hypothesis would also be consistent with the E–W flow direction suggested by Polet et al. [69] east of the Andean region based on a few SKS measurements near the Bolivia/Paraguay border.

Upper mantle anisotropy related to keel-deflected asthenospheric flow has been observed in eastern North America [20–23] and suggested for Australia [21,70,75]. In those two shield areas, complementary surface wave studies indicate that both lithospheric as well as APM-related asthenospheric anisotropy are present in the upper mantle, as proposed for central and SE Brazil. On the other hand, in southern Africa and east Africa, SKS splitting is better correlated with surface geological trends and is attributed to lithospheric deformation during the evolution of the Kaapvaal and Tanzania cratons, respectively [71,64,65,23]. Anisotropy beneath the cratonic lithosphere is very weak or likely absent. One possible explanation for this contrasted anisotropy pattern could be the much smaller absolute velocity of the African plate (less than 15 mm/y) compared to the South American plate which moves with almost 50 mm/y, according to the HS3 model [52]. A larger strain rate may result in a larger and possibly more localized strain below the lithosphere, favouring dislocation creep rather than diffusion creep and thus stronger crystallographic preferred orientation [14,21,23].

6. Conclusions

SK(K)S splitting observations in Central and SE Brazil are not uniform throughout the study region but reveal several areas with uniform fast polarization directions: WSW–ENE (Central Ribeira belt and northern Tocantins Province), E–W (central core beneath the Paraná basin, central Brasília belt and western border of the São Francisco craton), and NW–SE directions (southern Brasília belt and NE Paraná basin, on both sides of the Goiânia suture zone). In the central Ribeira belt and southern Brasília belt the fast shear-wave polarization direction is sub-parallel to the structural trend inferred from surface geology; the delay between the fast and slow S-wave arrivals is usually large and variable over short distances. These observations imply that a contribution of the lithospheric fabric to seismic anisotropy is very likely in those two domains. However, no clear correlation with geological trends is seen in the other areas.

The distribution of all observed fast polarization directions, over different geological provinces, has a peak in the E–W direction, close to the HS3-NUVEL1A model of absolute plate motion. A clear fan shaped pattern is observed around high upper mantle S-wave velocities (in the southern São Francisco craton and in a lithospheric block beneath the Paraná basin). These observations strongly suggest that the observed anisotropies have an important contribution from APM-related asthenospheric flow locally deflected by lithosphere/asthenosphere topography. A constructive interference of asthenospheric and lithospheric anisotropies is proposed for the southern Brasilia and the Ribeira belts.

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