Anisotropy of seismic waves in the Paraguay Belt from shear wave splitting analysis

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Abstract

The phenomenon of shear wave splitting allowed us to study the anisotropic behavior present in the lithosphere and asthenosphere beneath the Paraguay Belt – a folding belt with length of approximately 1000 km, located in southeastern Mato Grosso, which are recurring intense linear deformation – and its association to old and recent tectonic events in the region. The analysis of a range of seismograms containing SKS and SKKS phases, through the rotation-correlation (Bowman & Ando, 1987), eigenvalue (Silver & Chan, 1991) and minimum energy (Silver & Chan, 1991) methods were crucial to find the two main parameters associated to anisotropic behavior – fast polarization direction and delay time – for two layers and then discuss their possible relation to tectonics. It was used three seismographic stations (COXB, PRNTB, NVXB), which obtained results for the direction of fast polarization and delay time, respectively, 29º & 1.1 s, 37º & 0.5s, 36º & 0.6s to the lithospheric layer and 40º & 1.9s, 69º & 1.4s, 75º & 1.4s to the asthenospheric layer. These results might be related to the ancient orogenic processes as the drag between the lithospheric and asthenospheric layers as well as recent deformation due to the absolute motion plate. Due to strong consistency between the Mantle Flow Model, suggested by Conrad *et. al* (2007) and Absolute Motion Plate Model (Gripp & Gordon, 2002), it is believed that the anisotropy in the Paraguay Belt occurs mainly by convection of the mantle and plate motion.

Introduction

Seismic anisotropy describes the dependence of seismic wave velocity with the direction of propagation in the subsurface. In the upper crust this effect is caused by cracks and microcracks, multiple layers basement or highly foliated metamorphic rocks (Crampin, 1984). In the upper mantle is related mainly by preferred alignment of olivine mineral (LPO – Lattice Preferred Orientation) in the mantle relative to the direction of flow. Most of the lower mantle has isotropic information, except in layer D'' (Kendall, 1996). The inner core provides further indications of anisotropy according to Morelli *et. al* (1986).

In presence of anisotropy, there may be an effect compared to the birefringence of light phenomenon that happens when a polarized light beam travel through an anisotropic mineral such as calcite or quartz suffering double refraction with two refracted rays – fast and slow. Similarly to what happens to a beam, that phenomenon can also happen in shear waves, which can be divided into two waves with perpendicular directions and different velocities (the direction of higher speed known as fast polarization direction and the lowest speed known as slow polarization direction).

When exposed to simple shear in the upper mantle, the fast axis of olivine (axis-a) is oriented 45º of maximum shear direction. The simple shear rotates this axis to the infinite strain axis (ISA). However, the olivine crystals can also rotate with the flow, if the flow diverges from the simple shear (Figure 1).

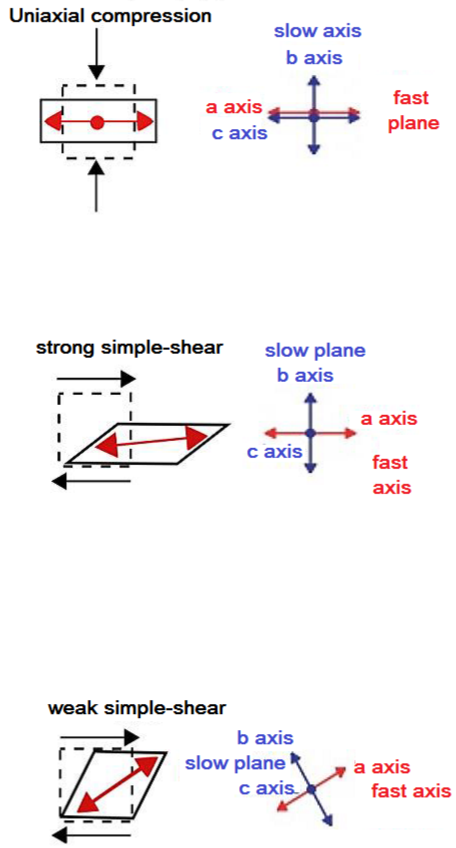

Figure 1 *– Preferred orientation in long-term dry olivine in simple shear and uniaxial compression deformation. Adapted from Dziewonski & Romanowicz (2009).*

The Paraguay Belt is a folding belt with length of approximately 1000 km and it is located in the southern part of the Amazon Craton, characterized by a large convex arch facing the craton which are recurring reverse and thrust faults, intense linear deformation and occurrence of granitic plutons in the inner area (Almeida, 1984).

In this context, anisotropic occurrences were observed below the Paraguay Belt through fast polarization direction and delay time in the shear wave splitting, trying to understand possible tectonic processes that permeated its formation, adding to global anisotropy studies.

Method

It was used teleseismic waveforms, containing the SKS and SKKS phases, gathered by three broadband seismographic stations (COXB, NVXB and PRNTB) belonging to the seismographic network deployed for studies of the Brazilian Lineament (LTB) (Figure 2).

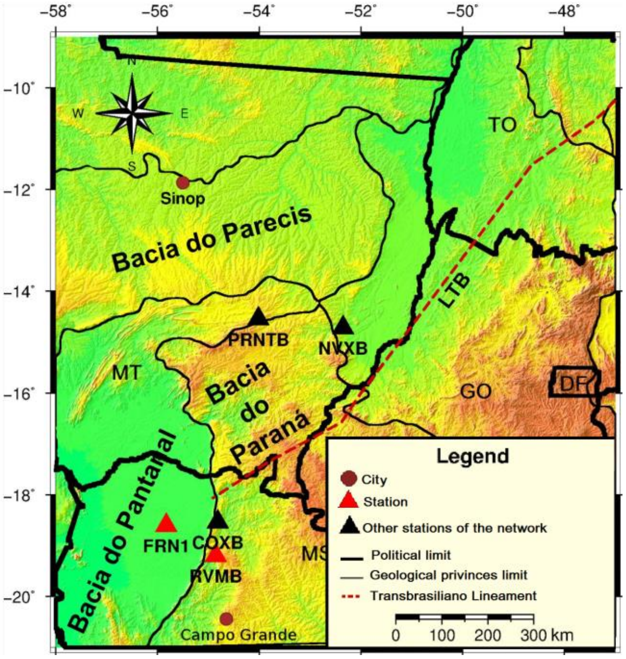

Figure 2 *- Seismographic network with stations used in this study.*

The teleseismic waveforms were processed in a MatLab^{TM} program code, Splitlab (Wüstefeld *et al.*, 2009), equipped with graphical interface. In order to remove the effect of splitting and thus find the fast direction and delay time, SplitLab uses simultaneously three different techniques, as shown in the Figure 3 – the rotation-correlation method (Bowman & Ando, 1987), the minimum energy method (Silver & Chan, 1991) and the eigenvalue method (Silver & Chan, 1991). In practice, these three methods consist of selecting the phase of interest on a seismogram window and rotating for Q-T components. Hereafter, it is made a time interval correction between the two waves and them the rotation of the seismogram in Φ and Φ + 90º at different angles in order to minimize the energy (RMS – root mean square) of the component Φ + 90º (Andrade, 2008). It was analyzed 212 seismogram readings at NVXB, 789 at PRNTB and 98 at COXB, comprising a period of data from January 1st 2012 to July 23 2012.

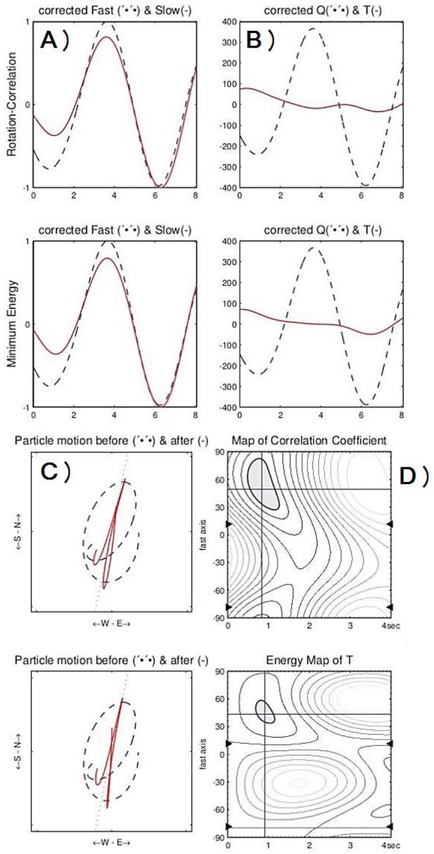

Figure 3 *– Example of determining the anisotropic splitting to SKS phase in PRNTB station. A) Maximum correlation of the signals from the fast and slow components. B) Q-T components, with the energy removal in T. C) Particle Motion before and after the correction. D) Correlation coefficient and energy maps in T component.*

Results

The results were given according to the proposal of Silver and Savage (1994), using the method of dual layer waveform inversion developed by Özalaybey and Savage (1994) in order to calculate the theoretical variation of anisotropy in two layers (Figure 4).

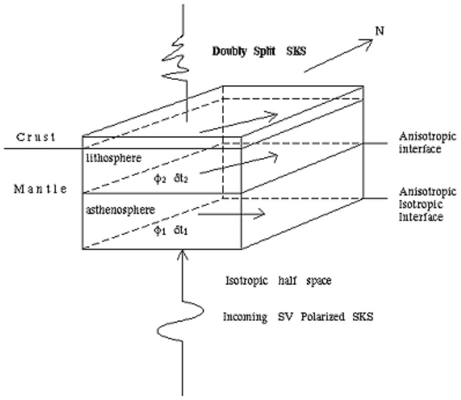

Figure 4 *– Anisotropy model with two layers. Taken from Özalaybey & Savage (1994).*

Considering only one layer, for a model with two layers with significantly different anisotropies, the value of anisotropy becomes apparent and azimuthal variations tend to occur. The properties of Φ_a and δt_a (apparent splitting parameters) are determined as a function of Φ_p and δt_p (parameters of individual layers) in order to find the splitting parameter (Φ_1, Φ_2 and δt_1, δt_2) for two layers (Table 1, Figure 5), by generating a synthetic sine function, given a fixed frequency ω. We considered the interface between layers in the lithosphere-asthenosphere limit, since the difference in the two anisotropic layers may have occurred in the change of rheological system.

Table 1 *– Results of fast polarization direction and delay time from a two layers model at the studied stations.*

	Φ_1(º)	δt_1(s)	Φ_2(º)	δt_2(s)
NVXB	36	0,6	75	1,4
PRNTB	37	0,5	69	1,4
COXB	29	1,1	40	1,9

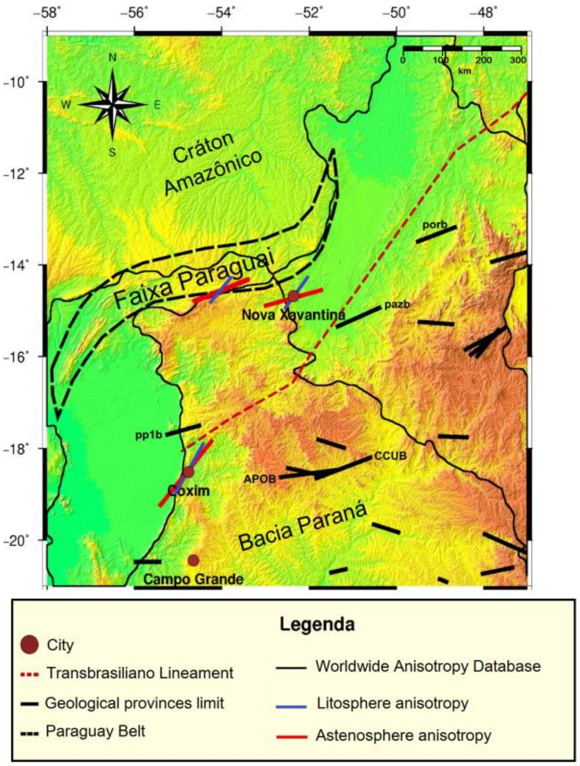

Figure 5 *– Anisotropic parameters for lithospheric and asthenospheric layers at COXB, NVXB and PRNTB stations. The vector's inclination indicates the angle of fast polarization direction in degrees and the vector's size indicates the delay time in seconds.*

The anisotropic values in the NVXB and PRNTB stations are similar to results obtained by other authors nearby the studied area (Table 2), considering the anisotropy measures in the lower layer given by the model of the double layer. The anisotropic values in the COXB station have questionable characteristic, probably because the anisotropy is null below the station or due to the low signal to noise ratio (SNR) in the seismograms.

Table 2 *- Comparison between the stations analyzed in this study and by other authors.*

Station Code	Lat. (º)	Long. (º)	Φ(º)	δt(s)	Author
NVXB	-14,7132	-52,3517	75	1,4	This work
PRNTB	-14,5400	-54,0147	69	1,4	This work
pazb	-15,1369	-50,8634	67	1,6	Assumpção *et al.* (2006)
COXB	-18,5328	-54,8183	40	1,9	This work
pp1b	-17,6003	-54,8797	75	1,2	Assumpção *et al.* (2006)
porb	-13,3304	-49,0787	70	1,4	Assumpção *et al.* (2006)
APOB	-18,5471	-52,0251	83	1,9	Assumpção *et al.* (2011)
CCUB	-18,4250	-51,2120	70	2,0	Assumpção *et al.* (2011)

Conclusions

Seismic anisotropy in the Paraguay Belt may be related to the lithospheric anisotropy due to ancient orogenic processes, such as anisotropy related to asthenospheric processes controlled by recent deformations from the drag between the two anisotropic layers (lithosphere and asthenosphere). In the upper layer (lithosphere) the results revealed directions of anisotropy parallel to the direction of Transbrasiliano Lineament, suggesting orogenic processes in common with the formation of both Paraguay Belt and Transbrasiliano Lineament (collision between the Amazon Craton and the São Francisco-Congo Craton – Brazilian/Pan African orogeny). Anisotropic effects due to past orogeny are shown generally parallel to the anisotropic directions. However, it can be influenced by tectonics and brittle strike-slip shear zones in the area, resulting in perpendicular directions to the drag, caused by the presence of type-B olivine. Considering the local temperature conditions, this situation is unlikely to happen. For the lower layer (asthenosphere), the results of the maximum anisotropy directions are approximately perpendicular to the Andes rock formation, suggesting the direction is related to the deformation between asthenosphere and lithosphere resulted from plate motion. In general, the anisotropy of Paraguay belt might be related to the joint of many effects as previously described. The anisotropic variations may occur due to more than one active process in the region, which can generate a set of active effects both in asthenosphere and lithosphere. According to Conrad *et al.* (2007), the fast polarization directions can be estimated by the mantle flow directions, or ISA directions. When deformation occurs for a long period of time, the direction of LPO is close to the direction of the ISA. Thus, the theoretical model of mantle flow, together with the theoretical model of absolute plate motion (Gripp & Gordon, 2002), would be one way to explain the source of anisotropy of the Paraguay Belt on a regional scale. Due to the strong consistency between the fast polarization directions with the directions of the mantle flow (ISA) and the absolute direction of plate motion, it is believed that anisotropy occurs in the Paraguay Belt mainly by convection effect caused by the mantle flow and deformations due to the recent plate motion (Figure 6).

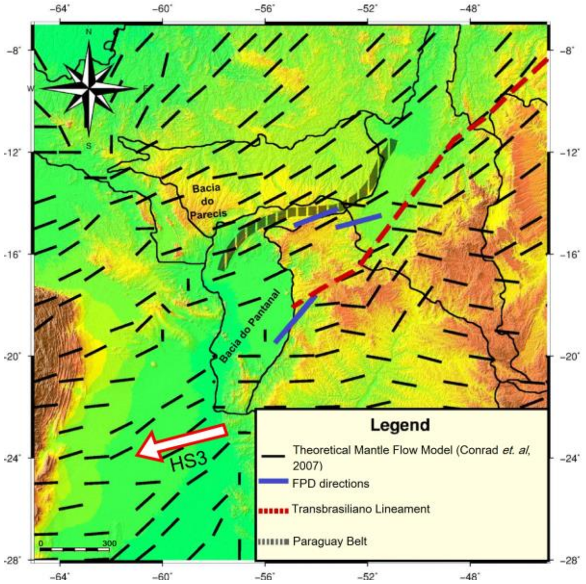

***Figure 6** – Comparison between maximum polarization directions (LPO) and infinite strain axes (ISA) relative to the absolute plate motion (HS3).*

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