Two-dimensional seismic refraction model of central Brazil crust

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Abstract

A two-dimensional model of central Brazil crust and upper mantle was obtained from travel-time interpretation of deep seismic refraction data from Porangatu, and Cavalcante lines. Moho is an irregular interface from 36 km to 44 km deep. Mean crustal V_P and V_P/V_S are, respectively, 6.6 km/s and 1.74 under Araguaia Belt, 6.5 km/s and 1.71 beneath Goiás Magmatic Arc, 6.4 km/s and 1.70 below Goiás Massif, as well as 6.4 km/s and 1.69 beneath the foreland fold-and-thrust belt, and western São Francisco Craton. The upper mantle presents V_P of 8.0 km/s under Porangatu line, and 8.3 km/s beneath Cavalcante line. Seismic features allow identifying: i) Neoproterozoic sutures related to a westwards subduction of São Francisco plate, and to an eastwards subduction of Amazon plate; ii) delamination of mafic-ultramafic root beneath Goiás Magmatic Arc; iii) thick skin tectonics in the foreland fold-and-thrust belt of northern Brasília Belt.

Introduction

This work presents a two-dimensional seismic velocity model for central Brazil crust and lithospheric mantle, as well as the mean Poisson ratio for the crust, obtained from travel-time interpretation of Porangatu and Cavalcante deep refraction lines performed in northern Goiás, central Tocantins Province (Fig. 1).

Porangatu and Cavalcante refraction lines, with a length of around 300 km each, and an overlap of 50 km, form a ca. 530 km long WNW-ESE seismic transect crossing the main geological units of Tocantins Province. From west to east starting in Araguaia Belt, the lines crossed Brasília Belt, passing through Goiás Magmatic Arc, Goiás Massif, and foreland fold-and-thrust belt, ending ca. 150 km inside São Francisco Craton. Each line was deployed separately with 120 recording points evenly spaced and a shot every 50 km. The explosive charges varied from 500 kg, in the center of the lines, to 1,000 kg in their extremes.

Geological setting

Tocantins Province was build up during Neoproterozoic Brasiliano Orogeny as the result of convergence of three major continental blocks represented by São Francisco/Congo, Paranapanema and Amazon cratons (Fuck *et al*., 1994; Pimentel *et al*., 2000; Araújo Filho, 2000). Along the lines the province comprises south Araguaia Belt bordering Amazon Craton, and the north branch of Brasília Belt at the western margin of São Francisco Craton. Brasília Belt is divided from west to east in Neoproterozoic Goiás Magmatic Arc, Archean/Paleoproterozoic Goiás Massif, and foreland fold-and-thrust belt, with Paleoproterozoic basement. The eastern 150 km is over São Francisco Craton (Fig. 1). Geological contacts are mainly tectonic discontinuities, represented by transpression zones, thrusts and reverse faults. From west to east they are the Transbrasiliano Lineament, Rio dos Bois fault, Rio Maranhão fault system, and Paranã fault.

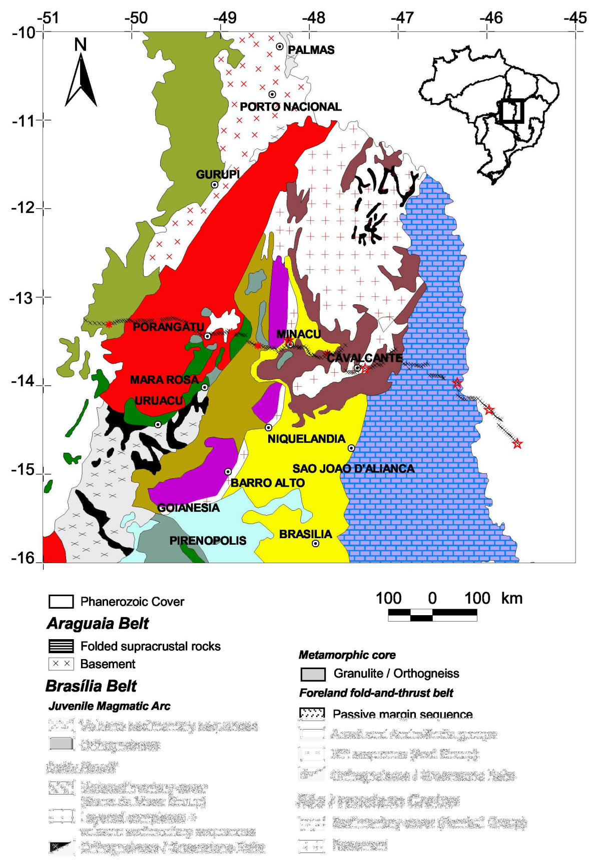

Figure 1 - Geological map of Tocantins Province, central Brazil. From east to west, are shown São Francisco Craton, Brasília Belt (foreland fold-and-thrust belt, Goiás Massif, and Goiás Magmatic Arc), and Araguaia Belt domains. Porangatu and Cavalcante deep refraction lines are almost perpendicular to main geological trend (after Fuck et al., 1994).

Travel-time interpretation

Deep refraction method is based on the interpretation of travel-time of first onsets and secondary phases in reduced sections with a reduction velocity between 6.0-8.0 km/s, and signals filtered in a band pass of around 1-20 Hz. Secondary phases, which appear in seismograms with easily identified clear amplitudes, are usually near critical angle reflections. Once the phases are determined and discriminated as refraction or reflection alignments, a preliminary model is elaborated, later on, improved through modeling process.

The following steps summarize the analysis performed with Porangatu and Cavalcante deep refraction data:

a) Primary and secondary P phases were identified on seismic sections, which have their time axis reduced with velocities of 6.0 km/s, 7.0 km/s, and 8.0 km/s, and filtered in a band pass of 1-15 Hz;

b) Time arrivals of refraction and reflection phases allowed elaborating preliminary models for each shot, using intercept time, and X^2-T^2 methods (Giese, 1976, Sheriff and Geldart, 1982);

c) An iterative one-dimensional modeling was obtained fitting the main phases (refractions and reflections) of each shot (Fig. 2). 1D modeling considers horizontal layers with velocity varying only with depth. Consequently, it does not determine real velocities of the medium and does not accommodate lateral discontinuities;

d) To obtain mean crustal V_P/V_S and Poisson ratio, Moho S reflections (SmS) were 1D modeled. To identifying SmS phases, reduced S sections were prepared with a reduction velocity, satisfying a V_P/V_S ratio of around 1.73, and with the time axis size scaled by the same factor (t_S/t_P~1.73), regarding the P section. P and corresponding S phases tend to occupy relatively the same position in the sections, improving S phase identification (Fig. 2; Table I);

e) 1D models were combined to develop a preliminary 2D model. A group of sequential 1D models, representing direct and reverse shots, permits to obtain real velocities approximation, to infer lateral discontinuities and dipping layers, leading to a preliminary 2D seismic model;

f) Finally, using the SEIS88 package (Cervený *et al.*, 1977), the preliminary 2D model was refined by iterative two-dimensional ray tracing modeling (Figs 3,4).

Model presentation and discussion

Cavalcante and Porangatu models permit to form a crustal profile of around 530 km across Tocantins Province and western São Francisco Craton in central Brazil (Figs. 1, 4). Despite geological differences, the crust under the refraction lines can be divided in upper, intermediate, and lower crust. The upper crust is formed by two layers and presents a variable depth between 9 and 16 km, V_P varies from 5.4 to 6.1 km/s in the first layer, and from 6.0 to 6.2 km/s in the second one. The intermediate crust corresponds to the third layer, with its bottom interface depth varying from 25 to 30 km, and V_P from 6.3 to 6.6 km/s. The lower crust presents two layers in both extremes of the profile, which are located below Araguaia Belt and São Francisco Craton, and just one layer in the middle portion of the profile. V_P varies from 6.7 km/s to 7.1 km/s in the lower crust, and Moho is an irregular interface with 36 to 44.5 km deep, with lateral discontinuities giving evidence of first order tectonic features. The upper mantle presents average velocity of 8.0 km/s below Porangatu line, and 8.2 km/s below Cavalcante line.

V_P presents smooth jumps between layers (< 0.4 km/s) and weak gradients inside them (~0.002 to 0.01 km/s/km). Calculated Poisson ratios (Table I) indicate felsic composition for the crust in central Brazil, including the lower crust of the Goiás Magmatic Arc. The exception is the bottom layer below the Araguaia belt, in the western part of the model, with V_P of 7.1 km/s and V_P/V_S larger than 1.8, indicating mafic composition, setting it apart from the rest of the province.

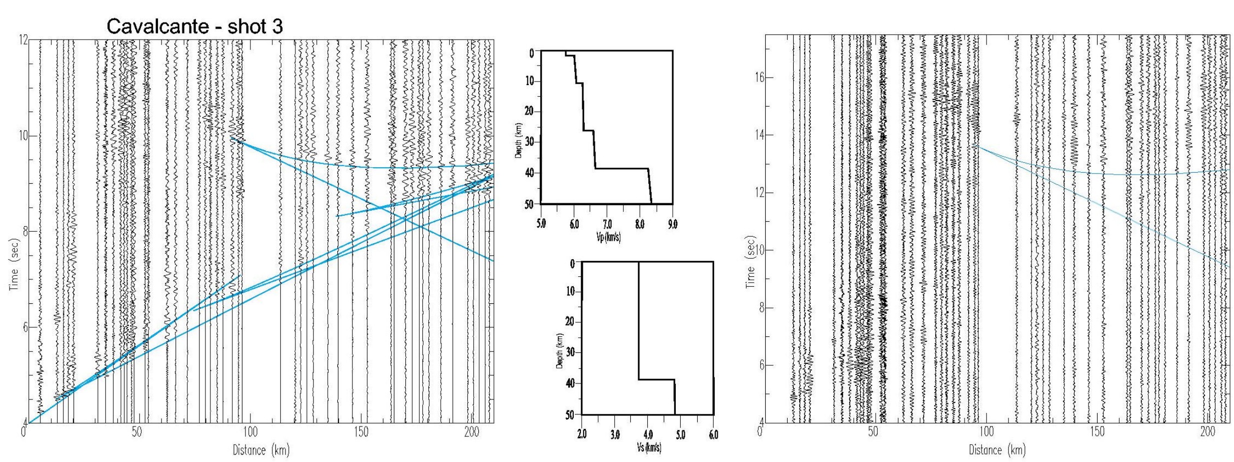

Figure 2 - Example of 1D modeling of P and SmS phases. P and S sections were filtered in 1-15 Hz and 1-10 Hz band pass, and reduced with velocities of 7.0 km/s and 4.1 km/s, respectively. Curves are synthetic results of 1D modeling of P and SmS waves in the model shown next to the seismograms.

Table I* - Mean seismic characteristics of Tocantins Province crust, central Brazil.

Seismic Domain	**Mean crustal Vp (km/s)**	**Mean crustal Vp/Vs**	**Poisson ratio (?)**	**Moho depth (km)**
Araguaia Belt	6.6	1.74	0.25	43
Magmatic Arc	6.5	1.71	0.24	36-38
Goias Massif	6.4	1.70	0.24	38
Foreland fold-and-thrust belt	6.4	1.69	0.23	44-41
São Francisco Craton	6.4	1.69	0.23	40-42

*from Soares et al. (2005b)

Evidence for lateral limits is mainly provided by i) depth discontinuities in the layers interfaces, ii) V_P discontinuities along the layers, which are accompanied generally by depth discontinuities in the interfaces; iii) changes in Moho geometry, which mostly coincide with first order tectonic features, and iv) mean crustal V_P/V_S variation. V_P/V_S is very sensitive to silica content and free of influences of geometrical complexity, being a valuable signature of main geological domains. The observation of at least two of these criteria together led to identifying crustal segments in central Brazil. Recognized crustal segments, from west to east, correspond to Araguaia Belt, Brasília Belt, divided in Goiás Magmatic Arc, Goiás Massif, and foreland fold-and-thrust belt, and western São Francisco Craton, including a transitional block at its western border.

Araguaia Belt is placed in the western end of Porangatu line, consequently, only the upper crust was constrained properly with seismic data. It can be differentiated from the adjacent Goiás Magmatic Arc terrain by variation in Poisson ratio, which indicates a more fractured and permeable upper crust under the Araguaia Belt (Melo *et al*., unpublished data). Araguaia Belt appears to include a mafic layer at the bottom of its lower crust. The crust displays, a mean crustal V_P of 6.6 km/s and V_P/V_S of 1.74. Excluding this bottom layer, the mean crustal V_P and V_P/V_S values are the same as in Goiás Magmatic Arc. This configuration is interpreted as the result of underthrusting of mafic lower crust of the Araguaia Belt below the magmatic arc. The step in Moho discontinuity, in the western portion of the section, is evidence of the eastwards subduction of Amazon plate in central Brazil. With the closure of the ocean basin, at the end of subduction, a piece of Amazon plate remained below Goiás Magmatic Arc as a fossil testimony of the subduction process.

Goiás Magmatic Arc is characterized as the thinnest crust of central Brazil, with its lower crustal layer dipping slightly eastwards (Fig. 4). Its mean crustal V_P is 6.5 km/s, and V_P/V_S is 1.71. Internally, beneath shot 3 of Porangatu line, there is a lateral velocity discontinuity, probably related to Transbrasiliano Lineament. This regional shear zone divides older arc rocks to the east from younger arc rocks to the west (Lima *et al*., 2003; Pimentel *et al*. 2004; R. Fuck *et al*., unpublished results). These younger rocks are probably the result of Amazon plate subduction and closure of ocean basin remaining between Amazon craton and Brasília Belt terrains to the east.

Mean crustal V_P of 6.5 km/s and V_P/V_S of 1.71, and lower crust V_P of 6.8 km/s, are surprisingly low values for a former island arc environment. These values do not match modern island arc terrains, which present mean crustal V_P around 6.7 km/s, and V_P/V_S 1.9 (Zandt and Ammon, 1995). The expected mafic lower crust related to the former island arc system is missing. A possible explanation could be that it was removed by delamination and/or slab break-off, leaving the felsic part behind, and making the crust beneath Goiás Magmatic Arc the thinnest crust of Tocantins Province.

The limit between magmatic arc terrains and Goiás Massif is well defined at surface by Rio dos Bois fault system, and inside the crust by lateral discontinuities of layers interfaces, and grid velocities variation. However, the western border of Goiás Massif is not evident in Moho surface, which is continuous, differently from other first order geological discontinuities recorded in Tocantins Province.

When crustal blocks of different geological histories are put together, a step in Moho, marking their suture, is an expected feature. A step records differences in crustal thickness of the sutured blocks, or crustal thickening, resulting from superposition of crustal segments, or even a combination of both. The lack of a step in suture zones, however, indicates possible reworking of lower crust and lithospheric mantle after suturing, homogenizing Moho relief in the process. The lack of a step in Moho between arc terrains and Goiás Massif suggests that the base of the crust of both terrains was reworked after collage. A possible explanation is that he inferred magmatic arc delamination affected also the Goiás Massif lower crust, homogenizing their contact.

Goiás Massif is considered to be an exotic terrain (Fuck *et al*., 1994; Pimentel *et al*., 2000, 2004) involved in the Goiás Ocean closing episode during Neoproterozoic time. During subduction of the ocean basin, it was squeezed between Goiás Magmatic Arc and the foreland fold-and-thrust belt terrain. The limit with the foreland fold-and-thrust belt is marked by a 7 km Moho step, which coincides with Rio Maranhão fault system, change in mantle velocity and with the gravimetric gradient observed in the central portion of the study area. Both crustal architecture and gravimetric anomalies change completely eastward of this conspicuous step, suggesting that it is a suture zone (Fig. 4).

Goiás Massif presents V_P of 6.4 km/s and V_P/V_S of 1.70, similar to the values found in the foreland fold-and-thrust belt (V_P of 6.4 km/s and V_P/V_S of 1.69). A possible explanation for V_P/V_S of 1.70 is that the massif was not constrained satisfactorily by seismic refraction data, due

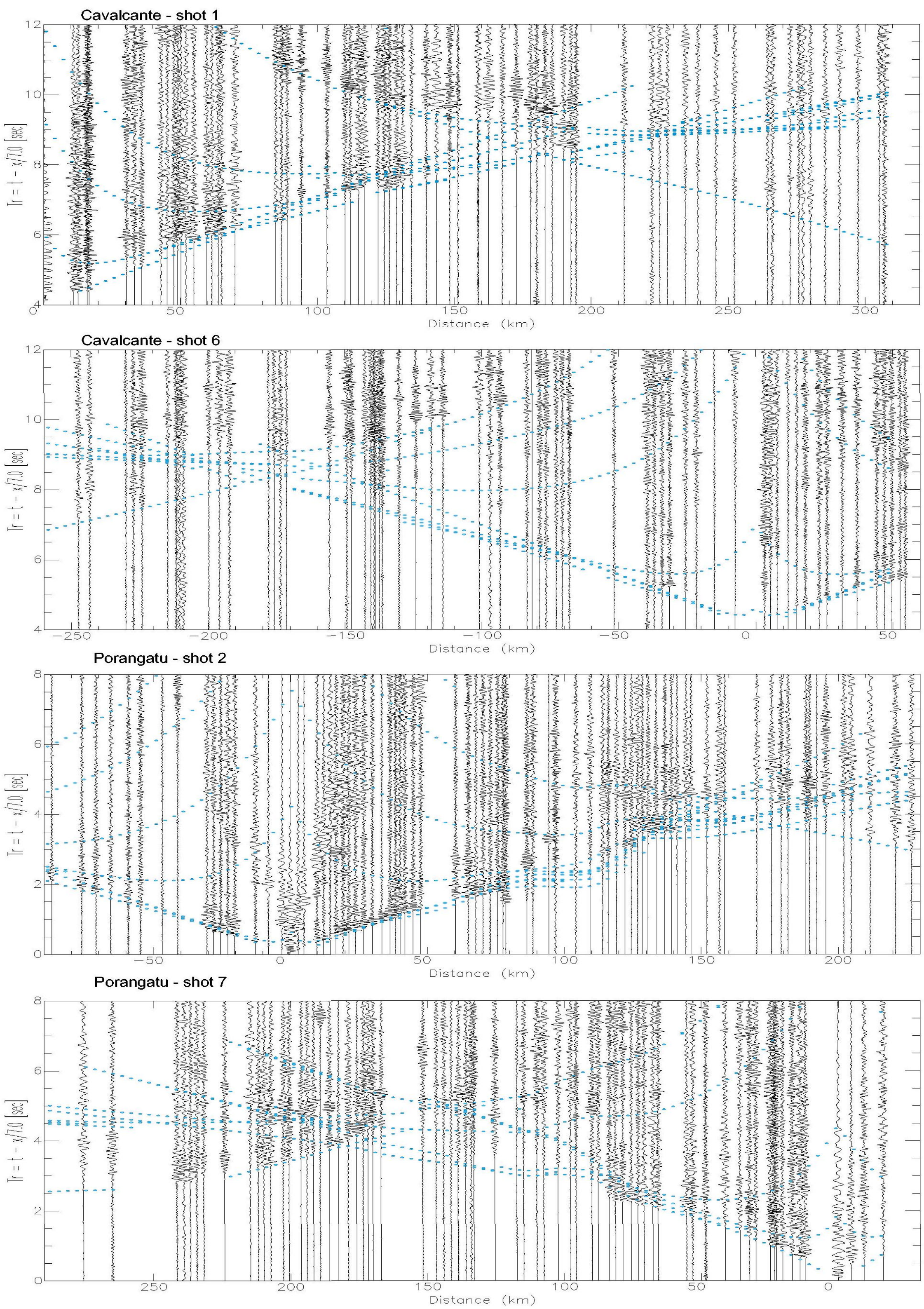

Figure 3 - Examples of direct and reverse seismic sections from Porangatu and Cavalcante deep refraction lines. Curves are synthetic results of 2D ray tracing of model of Figure 4. Sections are filtered in a band-pass 1-15 Hz and reduced by the velocity of 7.0 km/s. Complete seismic data set is shown and discussed in Soares *et al.* (2005a).

to its narrowness across the line (47 km). In this case the V_P/V_S value of 1.70 could be a transition value between foreland fold-and-thrust belt (1.69), and Goiás Magmatic Arc (1.71).

The foreland fold-and-thrust belt of Brasília Belt presents the thickest crust beneath central Brazil, with 44.5 km below Minaçu. Moho gets less deep eastwards from this point until Paranã discontinuity, which is the limit of the foreland fold-and-thrust belt with São Francisco Craton. The upper crust presents a block-structured pattern coincident with Araí rift domain. This geometry is not recorded in the lower crust. After the Araí rifting event (ca.1.77 Ma) this terrain underwent an extensional process giving birth to the Goiás Ocean basin (~1.0 Ma?). Later on, in Neoproterozoic time, Goiás Ocean closure and collision against São Francisco Craton led to shortening and deformation of the foreland fold-and-thrust belt. Eventual preservation of old structures is in agreement with low deformation imposed on Araí rocks, as observed in outcrops, suggesting that this region was affected mainly by block movement, during opening of Goiás Ocean and during its consumption in Brasiliano orogeny. This hypothesis is reinforced by the exposed basement northwards from Cavalcante line (Fig. 1), which seems to be an uplifted terrain, and also by the existence of the transitional block to the east.

The transitional block is characterized by crustal thinning, with Moho being shallower and surface topography being of lower altitude relative to adjoining areas. Topography forms a NS trough where Bambuí Group sediments overly basement rocks. This block was probably moved upwards during collision, followed by the erosion of Araí Group. Later on, Bambuí Group was deposited over the basement, and probably during Cretaceous time (after Urucuia Group deposition), the block was moved down, in a final adjustment that established a trough along São Francisco Craton border. The proposed fault limiting the transitional block with São Francisco Craton core is mainly supported by topographic and gravimetric data along ca. 440 km long lineament, since our model does not present a clear seismic discontinuity within the crust. Moho gets deeper eastwards, reaching 42.7 km in the eastern end of the model, without any sharp discontinuity. The middle and lower crust are continuous under the transitional block and São Francisco Craton, differing in this regard from the foreland fold-and-thrust belt crust.

A low velocity, low density, possibly silica rich body (V_P/V_S << 1.60) was identified through Cavalcante refraction line and receiver function data (Soares et al., 2004). It is placed between 30 km and 35 km of depth, close to Paranã discontinuity (Fig. 4). Cavalcante refraction line suggests a body 25 km to 30 km wide, and receiver function data identified its continuity to NNE, for at least 15 km from Cavalcante seismographic array, towards Paranã tin granites. Although identified, this body was not successfully modeled. We suggest that this anomaly is a high silica, low-density lower crust segment, which represents possibly the residue of source material of A-type granite magma related to Goiás Tin Province. Relationship of this anomaly with Moho shallowing and Paranã discontinuity, although suggested by their proximity, is not clear yet. Paranã fault acted probably as a channel of heat flow and melted rocks related to Araí volcanism, and A-type granite intrusions in late Paleoproterozoic and early Mesoproterozoic time.

Interpretation

The main subduction process in central Brazil was the relative westwards movement of São Francisco plate, subducting its oceanic lithosphere to form the island arc system west/northwestwards and below the Paranapanema Craton southwestwards. The island arc environment was formed during Neoproterozoic by subduction of oceanic São Francisco plate under oceanic Amazon plate. In this context, the small continental mass of Goiás Massif is considered as an exotic terrain producing a local disturbance/anomaly in São Francisco/Amazon subduction zone. Rio dos Bois fault marks the collage between Goiás Magmatic Arc and Goiás Massif, while the main suture seems to be related to the Rio Maranhão fault system, where Moho presents a step of 7 km coincident with the central gravimetric gradient, which records a sharp mantle discontinuity.

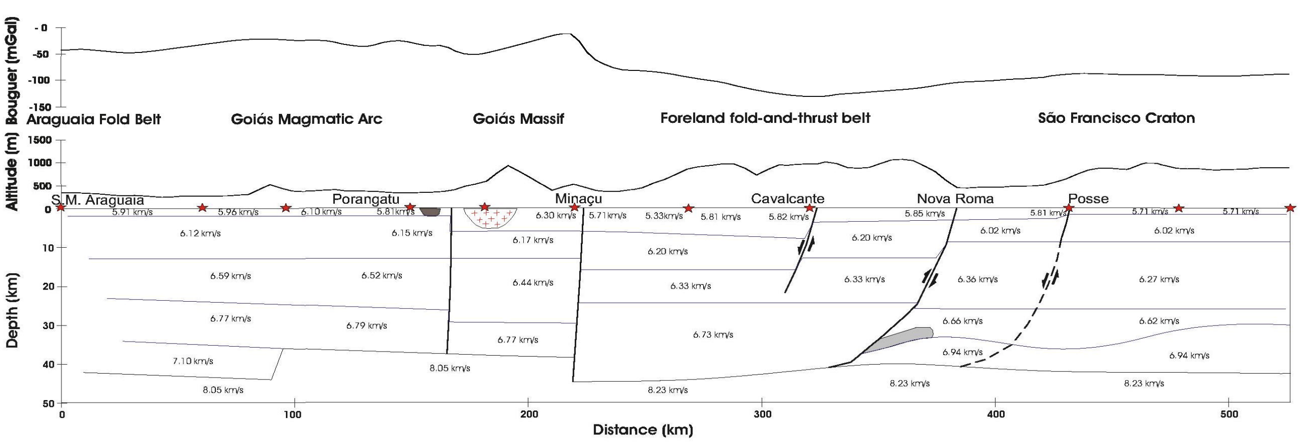

Figure 4 - Seismic model from central Brazil crust and upper mantle obtained from 2D modeling of Porangatu and Cavalcante deep refraction lines (Soares *et al.,* 2005). Topography and Bouguer anomaly profiles are also shown. See also Table I.

As a result of subduction, the crust in the island arc environment was differentiated in a felsic upper crust, in contrast with a mafic-ultramafic lower crust/lithosphere. The mafic-ultramafic part underlying the buoyant upper felsic crust in unstable equilibrium is generally denser than astenospheric mantle. As São Francisco oceanic crust was completely consumed, subduction got inverted, with the oceanic part of Amazon plate starting to be consumed eastwards. Apparently, inversion of subduction triggered rupture of Goiás Magmatic Arc lithosphere. Its mafic-ultramafic part uncoupled and foundered within the mantle. Removal of mafic-ultramafic lithosphere led to upwelling of hot asthenosphere material, which uplifted thermally the arc terrain and homogenized Moho discontinuity at the limit with Goiás Massif. Later on, when thermal equilibrium was restored, Moho became shallow, and erosion reduced topography to its present low level. Geophysical evidence of Amazon subduction and its related features in central Brazil are discussed with more detail in Soares *et al*. (2005b).

Conclusions

Seismic results obtained in this work match main surface geological limits, confirming division of the crust in central Brazil, from west to east, in Araguaia Belt, Goiás Magmatic Arc, Goiás Massif, foreland fold-and-thrust belt, and São Francisco Craton domains, the latter including a transitional block in its western margin. Poisson ratio and V_P values define the crust beneath the study region as of felsic composition, except for the bottom layer under Araguaia Belt, which is mafic in composition.

Neoproterozoic São Francisco plate subduction westwards was the first convergent event, and Amazon plate subduction eastwards was the second one. In this process Goiás Massif was squeezed between Goiás Magmatic Arc and foreland terrains, which is considered a local anomaly disturbing regional São Francisco subduction zone.

The foreland fold-and-thrust belt domain together with the transitional block seems to define thick skin tectonic in north branch of Brasília Belt during Goiás Ocean opening and closing, in Neoproterozoic time.

Delamination of mafic-ultramafic root beneath northern Goiás Magmatic Arc was a catastrophic step in central Brazil geological history. Main evidence of this episode is the lack of a lower mafic crust below Goiás Magmatic Arc associated with thin crust and deeply eroded topography.

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