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Tectonic evolution of the Paleozoic Alto Tapajós intracratonic basin - A case study of a fossil rift in the Amazon Craton

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ABSTRACT

The Alto Tapajós Basin is an intracratonic basin located in the Amazon Craton, consisting predominantly of Paleozoic siliciclastic sedimentary rocks cutted by Mesozoic dyke swarms. With an area of about 97,000 km^2, the size of Portugal, some parts density cover by the Amazon forest, it has few detailed studies regarding geological structures and potential for hydrocarbons, with scarce surface mapping, absence of seismic surveys and only one well drilled to the SE. It is a NW-SE oriented branch of the ENE-WNW Amazonas Basin. Geological maps, topographic, gravimetric and magnetometric data are here interpreted and integrated to analyse its tectonic evolution. The sedimentary strata are deposited on reactivation zones related to NW-SE normal faults and NNE-SSW oblique faults, that control the spatial arrangement of the basement highs. The former is parallel, and some places coincident, with a major tectonic Paleoproterozoic crustal boundary that separates the Tapajós-Parima and Rondônia-Juruena provinces within the Amazon Craton. The NNE-SSW oblique faults are interpreted as representing a transfer zone that accommodates the Paleozoic oblique rifting mode. However, the rifting age is still not well stabilised. Cambrian mafic dikes could link the initiation of this basin to the breakup of a supercontinent in the early Cambrian (Pannotia), in the dawn of the Gondwana. To account for the Devonian to Permian basin subsidence, crustal stretching due to intraplate passive rifting might have played the role, in response to farfield stresses regarding a convergent tectonic setting on the western margin of Gondwana (Terra Australis and Alleghanian orogenies). This is corroborated by the shift on the basin depocenter axis, from NW-SE (Devonian-Carboniferous) to NNE-SSW (Permian), that might be related to the change on orientation of stresses due to these two orogenies. In addition, the Paleozoic sedimentary units occur basically within the same area of the Paleoproterozoic cratonic sedimentary units from a ca. 1.7 Ga rift. This suggests that the Alto Tapajós Basin Paleozoic rifting reactivated an ancient fossil rift, also described in other cratons throughout the world. In the Jurassic, Alto Tapajós Basin was submitted to a post-sedimentation tectono-thermal event, related to the disintegration of Pangea and expansion of the Central Atlantic Magmatic Province (CAMP). During this episode, 180–220 Ma mafic dike swarms intruded its central-southwest compartment, following the NNE-SSW structures. The actual positive topographic feature, Cachimbo Range and plateau, and the absence of thick Cenozoic deposits, unlike the Amazonas Basin, indicate that the recent evolution of the Alto Tapajós region is related to uplift within an intraplate setting.

1. Introduction

Continental rifts that do not evolve into oceanic crust become fossil rifts, setting opportune tectonic environments for the development of intracratonic basins. Subsidence processes in cratonic areas are generated by variations in the direction of deformation at lithosphere, usually related to orogenic events in neighboring belts (Ingersoll, 2012). Subsidence occurs when lithospheric rigidity is attenuated, allowing uncompensated mass in the upper crust, related to the remnants of the fossil rifts, to subside over a large region, due to reactivation of

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ancient crustal structures. However, during periods of non-orogenic activity, lithosphere stiffening occurs and a concomitant interruption of the isostatic equilibrium process takes place (Ingersoll, 2012).

With the only exception of its northwestern border, where it merges into the Amazonas Basin, the Alto Tapajós Basin is limited and structured on the basement rocks of the Amazon Craton. It is consisted of Paleozoic sedimentary successions, predominantly siliciclastic, cutted by Mesozoic basic intrusive rocks. Although covering an area of approximately 97,000 km^2, equivalent in size to Portugal, this sedimentary basin has never been subject of detailed studies, evidenced by scarce surface mappings and wells.

The existence of a rift under the Alto Tapajós Basin was first proposed by Siqueira (1998), based on the evaluation of gravimetric and magnetometric data integrating with field data. According to Brito Neves et al. (1984) and Teixeira (2001), this perception is repeated for other Brazilian Paleozoic Basins, such as Amazonas, Parnaíba, Paraná and Parecis basins. In these were identified excellent correlations between seismic sections and gravimetric and magnetic anomalies, which reinforce the idea about fossil rifts preceding the Paleozoic syneclises. However, unlike the great Paleozoic Gondwana basins, developed on Cambro-ordovician rift systems, the Alto Tapajós Basin seems to be stabilished on a Paleoproterozoic rift structure within a major suture zone of the Amazon Craton.

The main proposal of this paper is to characterize the structural framework of the Alto Tapajós Basin and its relation with the basement fabric, using topographic, geological and geophysical data. The integration and interpretation of this data will provide insights on the origin and tectonic evolution of this poorly known intracontinental Paleozoic basin.

2. Overview of regional geology and tectonics

2.1. The Amazon Craton basement

Composed by Archean microcontinental cores, Paleoproterozoic and Mesoproterozoic mobile belts (Schobbenhaus and Brito Neves, 2003), the Amazon Craton is divided in several provinces mostly regarding geochronological data from U-Pb and Sm-Nd studies (Santos et al., 2000). These provinces were characterized with results of systematic geological mapping made by the Geological Survey of Brazil (CPRM). It is clear that the Amazon Craton evolved from southeast, where lies the oldest Archean nuclei (Carajás Province) to the north and the west, towards the youngest Mesoproterozoic Sunsás Province (Fig. 1).

The Alto Tapajós Basin occurs in the boundary between two major geochronological provinces (Fig. 1). To the northeast, the Tapajós-Parima Province composed of 2.03–1.87 Ga calc-alkaline vulcano-plutonic rocks, interpreted as Orosirian magmatic arcs, with minor metassedimentary units (Santos, 2003). NW-SE km scale lineaments correspond to subvertical strike-slip faults with sinuous tracing, interpreted as shear zones associated to Tapajós Transcurrent Faults Megassystem (Santos, 1999). Some of these structures subdivide the Tapajós-Parima Province into blocks and could be traced below the Alto Tapajós Basin (Coutinho, 2008).

To the southwest, the Alto Tapajós Basin is in contact with Rondônia-Juruena Province, characterized by volcanic and sedimentary lithological groups, cross cutted by anorogenic granites and overlain by metassedimentary rocks of the Beneficente Group (Santos, 2003). Its main structural trend abides to NW-SE and E-W folding axes (Santos, 2003). The magmatic units are interpreted as two continental margin arcs related to the collision of the Paraguá protocraton and the Tapajós-Parima Province (Scandolara et al., 2017).

In addition, the southeastern tip of the Alto Tapajós Basin covers partially the NNW-SSE Central Amazon Province (Fig. 1), which is dominated by Paleoproterozoic rocks that show a magmatic province of 1.88–1.87 Ga (Santos, 2003).

2.1.1. Paleoproterozoic sedimentary basins

Sedimentary rocks of Paleoproterozoic age compose a notable section of shield areas surrounding the Alto Tapajós Basin constituting part of its basement. Among these sequences are the Beneficente and the Buiuçu groups, exposed in Rondônia-Juruena and Tapajós-Parima provinces, respectively (Fig. 2).

The Beneficente Group is a sequence of marine sediments represented by sandstones, siltstones, and local intercalations of conglomerates (Lacerda Filho et al., 2001). Zircons from pyroclastic beds, interleaved with the sequence, gave an age of 1691 ± 73 Ma for the volcanic event (Santos et al., 2000). This group is tilted with beds striking NW-SE and E-W, controlled by sinistral shear zones (Souza et al., 2005). Locally, in the northern escarpment of the Cachimbo Mountain Range, the Beneficente Group sits unconformably on volcanic rocks (Fig. 2a). Its maximum age is between 1.7 and 1.9 Ga, according to Pb/Pb ages on detrital zircons of the basal conglomeratic facies interpreted as derived from alluvial fans and sandy rivers of interlaced pattern (Saes et al., 2006). Its sources are the surrounding acidic to intermediate volcanic rocks and the Archean nuclei of the Central Amazon Province to the east. In the southern escarpment of the Cachimbo Mountain Range, the basal unit is covered by fine clasts and carbonates, which were deposited in an epicontinental marine environment (Saes et al., 2006).

The Buiuçu Group, exposed in the upper courses of the Tapajós River, contains arcosean sandstones and conglomerates, as well as minor siltstones and tuffs, interpreted as deposited in a continental braided system (Reis et al., 2006a). It occurs as a NW-SE strip, with sharp contact with Devonian to Lower Carboniferous and Upper Carboniferous to Permian sedimentary formations of the Alto Tapajós Basin (Fig. 2). Its minimum age was estimated at around 1.778 Ga, according to U-Pb data from baddeleyite in basic intrusive rocks (Santos et al., 2000). The contact between the Buiuçu and Beneficente groups is covered by the Paleozoic sedimentary strata, therefore unknown.

2.2. The Amazonas Basin

To the north, the Alto Tapajós Basin is in contact with the southwest area of the Amazonas Basin (Figs. 1 and 2). The latter is a major WSW-ENE oriented intracratonic sedimentary basin with a stratigraphic pile of more than 5000 m comprised by Paleozoic sedimentary formations and Mesozoic igneous sequences (Cunha et al., 2007). Cenozoic sedimentary units predominantly cover large areas of the basin, including its possible connection with the Alto Tapajós Basin (Fig. 1).

Wanderley Filho (1991) recognizes five major NW-SE oriented faults, Manacapuru-Rio Negro, Urubu-Crepori, Faro-Juruti, Paru-Anapu and Pari-Pacajai (Fig. 2) that segment Amazonas Basin into four distinct blocks. These domains might have controlled the distribution of the sedimentation through time in between structural highs generating unconformities (Fig. 2). One example is the absence of Devonian units in its westernmost compartment. In comparison with the Ordovician and Permian-Carboniferous units, the Devonian sedimentary rocks decrease in thickness towards the Purus Arch (Fig. 2a). Because of this evidence, Wanderley Filho (1991) suggests that the Purus Arch region acted occasionally as a structural high in the Paleozoic, which might have isolated the Alto Tapajós Basin (Fig. 2).

The connecting region of the Amazonas and Alto Tapajós basins has up to 250 km lenght of NW-SE lineaments (Fig. 2). Wanderley Filho (1991) interpreted them as critical normal faults related to the formation of the so-called Cachimbo Graben (Fig. 2a). NW-SE regional extensional structures have similarly been described in the Purus Arch (Fig. 1), which is also recognized in seismic and geological sections and gravimetric and isopach maps, configuring the boundary amid Amazonas and Solimões basins (Mabesoone and Neumann, 2005). According to similarities observed in the structural fabric, it is established that the Purus Arch consists, jointly with Cachimbo Graben, an equal tectonic feature (Fig. 2a).

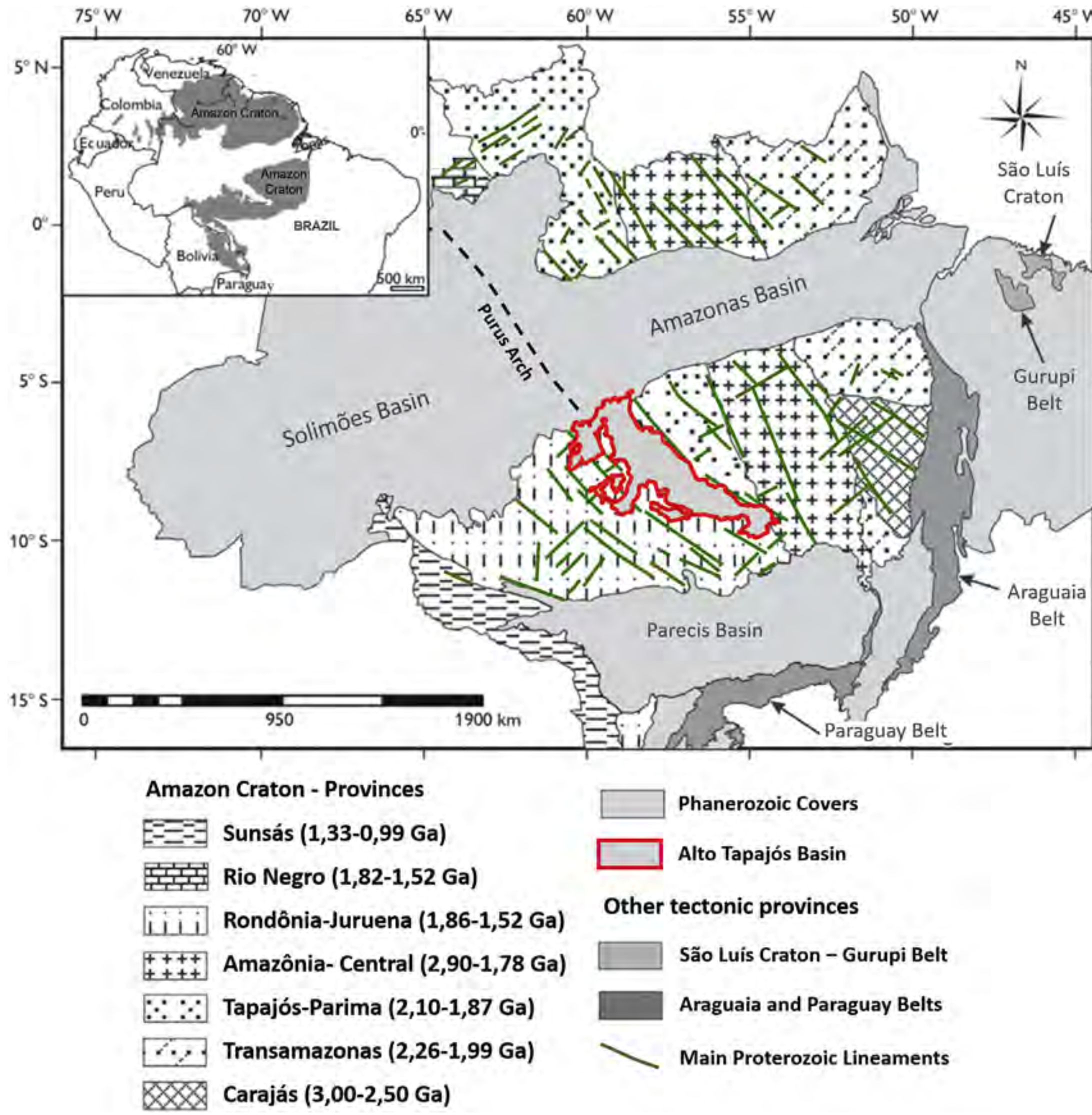

Fig. 1. Location of the Alto Tapajós Basin (in red line) within the geochronological provinces of the Amazon Craton, according to Santos (2003) and adapted from Queiroz et al. (2016). Highlight for the main lineaments of Proterozoic age of the Amazon Craton, according to Wanderley Filho (1991) and modified from Barbosa (2010). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

This regional NW-SE structural framework is also observed with geophysical data. Lloyd et al. (2010), from analysis and processing of sparse seismological geophysical data from Amazon Craton, interpreted a NNW-SSE crustal thickening zone, from central region of the Guiana Shield to the eastern portion of Central Brazil Shield (Fig. 3). Rosa et al. (2016) associate this thickened region as evidence of Paleoproterozoic magmatic arcs. Underneath the Alto Tapajós Basin, Moho's depth is estimated between 37 and 47 km. A secondary NE-SW trend of crustal thickness is observed in the central part of the Alto Tapajós Basin (Fig. 3), coincident with regional fracture system associated to a dolerite dike swarm described in the west part of the Tapajós-Parima Province (Coutinho, 2008). Such areas of juxtaposed contrasting lithospheric architectures present numerous opportunities for lithospheric instabilities, being susceptible to reactivation during assembly and dispersal of supercontinents (Aitken et al., 2013).

2.3. *The Alto Tapajós Basin*

2.3.1. *Stratigraphy*

Over the last few decades, some stratigraphic charts have been proposed for the Alto Tapajós Basin, but the lack of geological mapping and subsurface data make these far from an agreement (Teixeira, 2001; Santiago et al., 1980). Comprising an extensive area on the border between the Brazilian states of Amazonas, Pará and Mato Grosso, most stratigraphic data of the Alto Tapajós Basin come from its central portion, which is accessible by Tapajós River drainage system and by the confluence zone between Juruena and Teles Pires rivers. Some land accesses are possible from roads that cross the northwest and southeast ends of the basin (Fig. 4).

The stratigraphy established by Santiago et al. (1980), based on surveys carried out along the BR-230 road and the Juruena River (north and central areas of the basin), presents Proterozoic and Paleozoic formations with more than 1700 m of thickness. They divided the Paleozoic record into five formations from the base to the top: Borrachudo, Capoeiras, São Benedito, Ipixuna and Navalha. However, according to the analysis of lithological data from a drillhole (Lopes, 2001) in the southeast region of the basin (UTM coordinates 8,966,491.2 N/712.362,5 E), the presumable Paleozoic sequence presents a thickness of only 147 m (Fig. 5). Teixeira (2001) also divides the sedimentary sequence in two distinct age intervals: Proterozoic Megassequence and Paleomesozoic Megassequence.

Reis et al. (2006b) identified three sedimentary units for the Alto

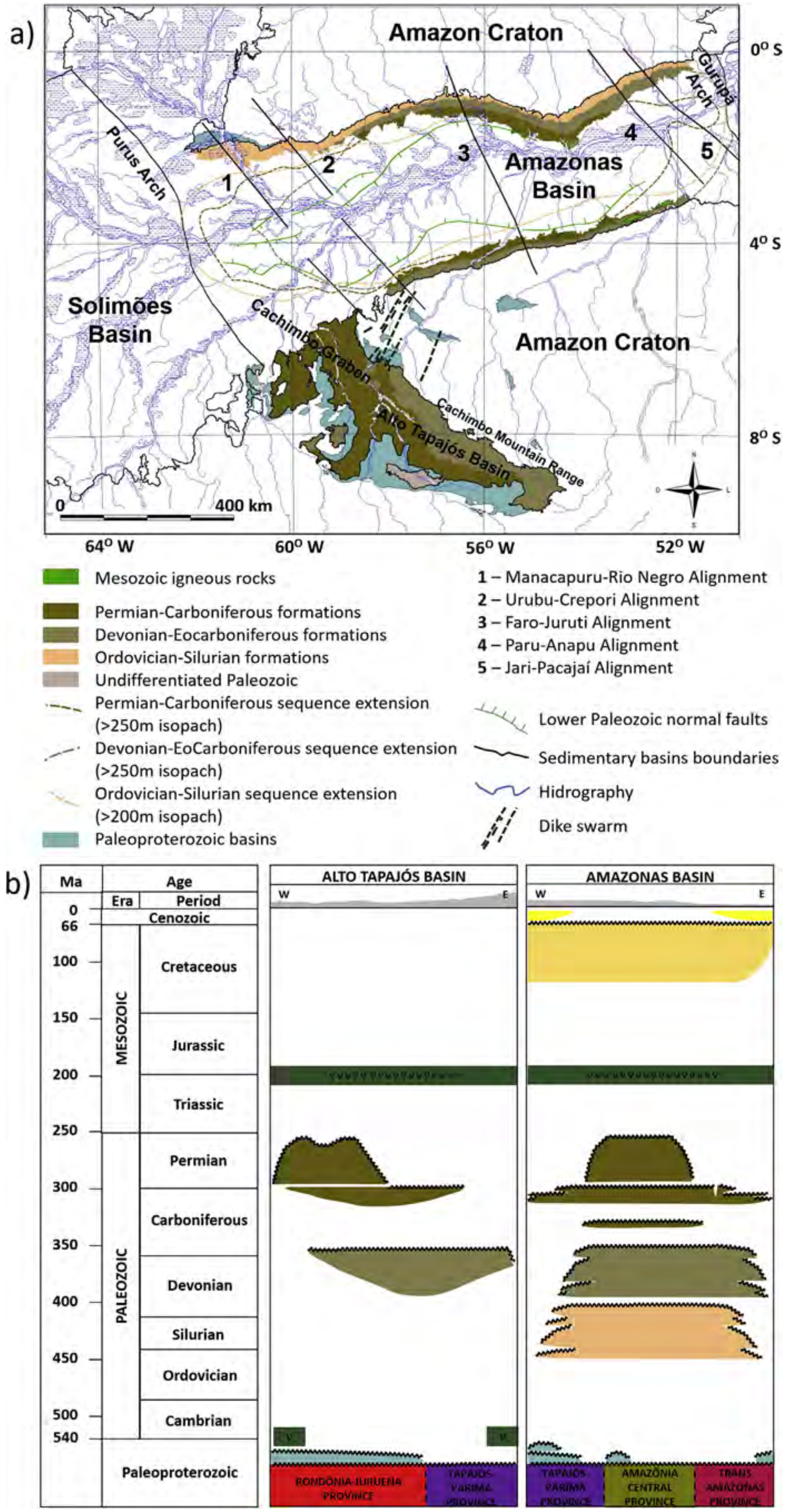

Fig. 2. a) Main structures and stratigraphic units of Amazonas and Alto Tapajós basins (modified from Wanderley Filho, 1991). b) Proposed chronostratigraphic charts of Alto Tapajós e Amazonas basins (modified from Cunha et al., 2007).

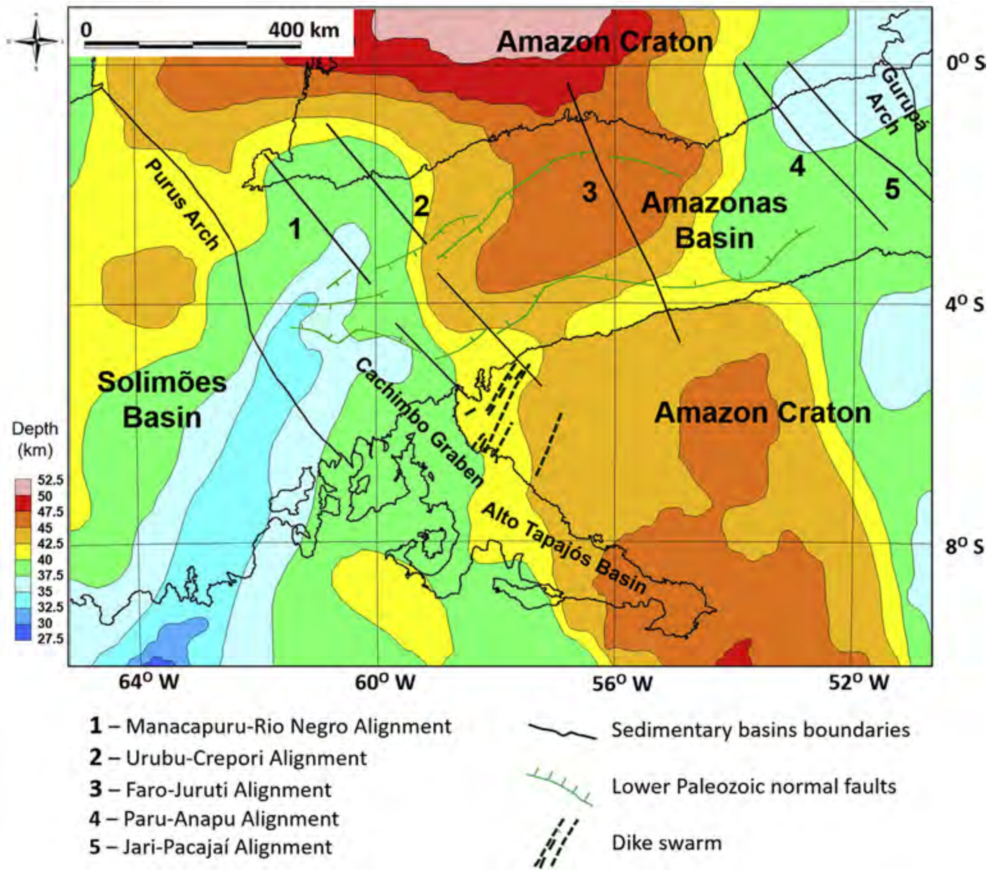

Fig. 3. Crustal thickness map of the Amazon Craton. Note NW-SE framework of Alto Tapajós and Amazonas basins. Estimation of Moho's depth obtained from analysis and processing of seismological geophysical data. Modified from Lloyd et al. (2010).

Tapajós Basin in the upper reaches of the Tapajós River. The basal unit is characterized by continental sandstones. The intermediate unit, the Jatuarana Group, encompasses the Paleozoic sedimentary sequence, being related to fluvial-deltaic, tide-influenced and shallow marine environments. The unit at the top corresponds to fluvial sandstones of possible Pleistocene age, outcropping in the low course of the Teles Pires River. This publication considers only the Paleozoic range as an integral part of the Alto Tapajós Basin (Fig. 4), according to the stratigraphy adopted on the following sheets of the Geological Map of Brazil 1:1.000.000 scale: SB.20-Purus, SB.21-Tapajós and SC.21-Juruena. Unfortunately, there are no formal taxonomy and systematic publications on the biostratigraphy of these formations. Only Riker and Oliveira (2001) and Reis et al. (2006b) describe microfossils and plant fragments.

The Devonian-Lower Carboniferous sequence, defined by intercalation of sandstones and siltstones (Figs. 2 and 6), is interpreted as deposited in a transitional environment between continental, shallow marine and fluvial-deltaic with tidal influence, with ripple marks, cross bedded and ichnofossils (Reis et al., 2006b). Riker and Oliveira (2001) confirmed the Devonian age of the basal units due to the identification of sporomorphs (*Caliptosorite* cf. *velatus*, *Verrucosisporites* cf. *nitidus*, *Geminispora* sp., *Secariosporite* sp., *Aurorospora* sp., *Apicularetusispora* sp. and *Retusotriletes* sp.) in sandstones on Sucunduri River, at the southwest end of the basin (Fig. 4). However, the total absence of pollen and the presence of spores *Calamospora*, *Reticulatisporites*, *Verrucosisporites* and *Convolutispora* in the São Benedito Formation open the possibility that this formation can be of early Carboniferous age (Lima and Sundaram, 1982). Therefore, a late Paleozoic age is attributed to the upper units of the Alto Tapajós Basin.

The Permo-Carboniferous sequence is characterized by mudstones and sandstones, with subordinate siltstones and limestones (Fig. 6) interpreted as deposited in a fluvial-deltaic and a shallow marine environment (Reis et al., 2006b). Reis et al. (2006b) record the Paleozoic age of the sedimentary rocks on the banks of the Tapajós River and the Juruena River (Fig. 4), evidenced by occurrences of palynomorphs and plant fragments in the regions of Morro São Benedito (*Dyctiotriletes* sp. and *Dibolisporites* sp.) and Serra da Navalha (myospores).

2.3.2. Magmatic events

The Amazon Craton experienced meaningful tectonomagmatic activity during the Mesozoic Era, testified by dikes, sills and laccoliths of mafic basic rocks and alkaline bodies. Lima and Bezerra (1991) suggest a structural control for these bodies, guided by the reactivation of structural highs and Precambrian structures.

The occurrence of mafic dikes in the northeastern area of the Alto Tapajós Basin within its surrounding basement is attributed to a rifting process that generated this basin after the Brasiliano tectonic events. Santos et al. (1999) present U-Pb ages in baddeleyite of 514 ± 15 Ma for these rocks, proposing a Mid-Cambrian tectonic-magmatic event, so called Piranhas Magmatism (Fig. 4). Tassinari (1996), on the other hand, identifies Ediacaran age dolerites (565 ± 6 Ma, K-Ar method) in a southwest cratonic area (Fig. 4).

Dolerites on the Cachimbo Range (Fig. 4), with more than 400 km lenght, were dated between 180 and 220 million years (K-Ar method - Lima and Bezerra, 1991). They related these swarms to the reactivation of the Juruena Arch, in the Rondônia-Juruena Province (Fig. 4).

2.3.3. Geological structures and tectonic evolution

From studies of lithostructural interpretation based on radar and Landsat images, sedimentary layers of the Cachimbo Plateau show a predominant WNW-NW strike dipping to SW (Lima, 1986) close to its north escarpment. Towards the southwestern flank of the plateau, the

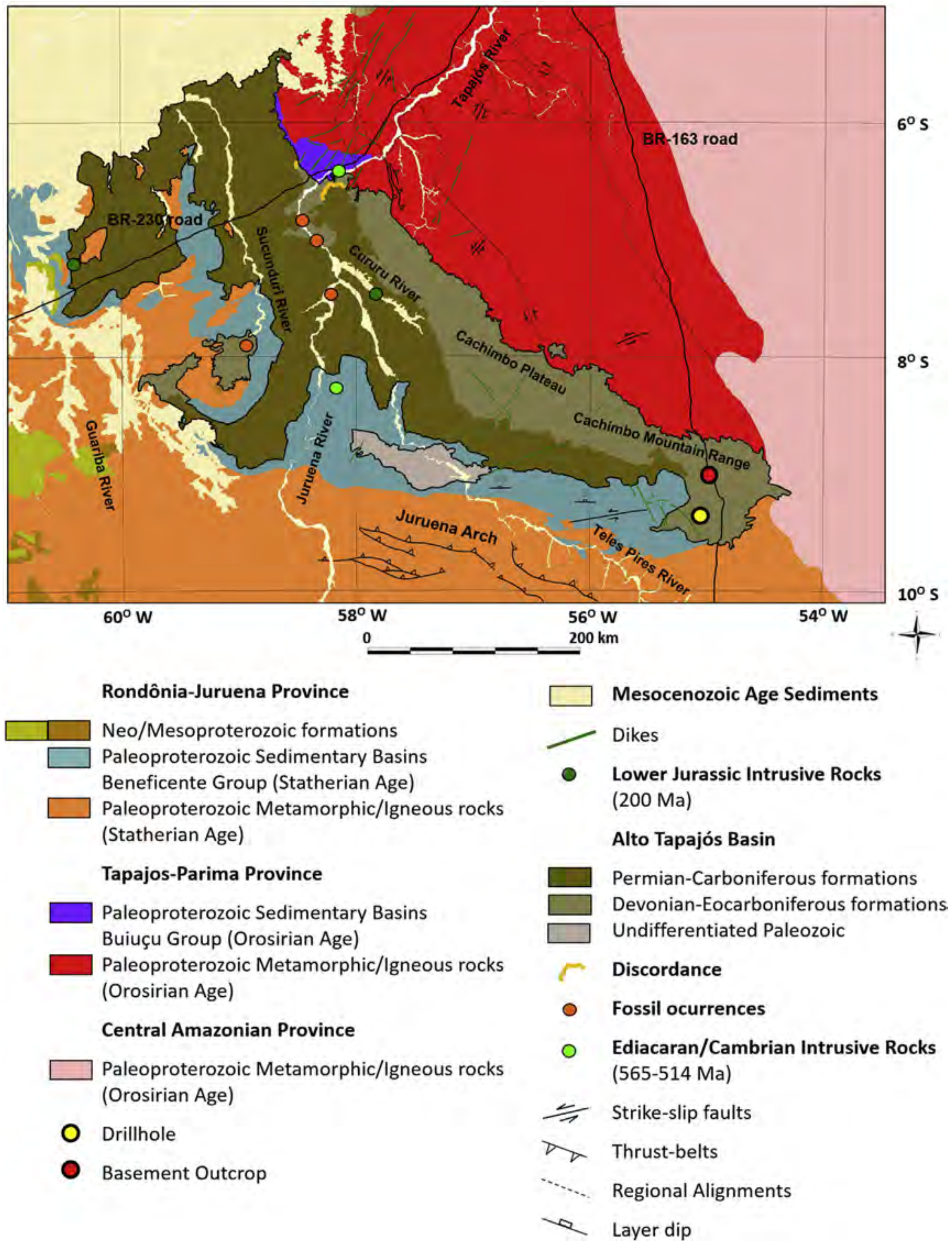

Fig. 4. Simplified geological map of the Alto Tapajós Basin and surrounding cratonic provinces. This figure was adapted from the Geological Map of Brazil 1:1.000.000 scale (2004). The ages from the intrusive igneous rocks are from Santos et al. (1999) and Tassinari (1996).

structural framework is interrupted by gentle E-W folds within the rocks of the Beneficente Group. Another significant feature is a N-S dike swarm, related to normal faults interpreted in the southern flank of the Cachimbo Plateau and east of the Sucunduri River (Fig. 4).

Several events are indicated for the tectonic evolution of the Alto Tapajós Basin. Costa and Hasui (1992) attributed an evolution in three distinct stages for the Cachimbo Graben (Figs. 2 and 3). The first stage refers to the formation of a rift or aulacogen characterized by symmetrical structures, crustal thinning, depression of blocks controlled by NW-SE high angle faults and associated magmatism, and NE-SW transfer faults. The second stage corresponds to a syneclise, with slow downward bulge, affecting the rift domain and adjacent areas. The third stage is associated with a very slow subsidence process, marked by the development of horizontal tabular sedimentary cover.

3. Results

The integration of geophysical, geological and topographic data is essential for understanding the structural framework of the Alto Tapajós Basin. We compiled a wide range of data from different

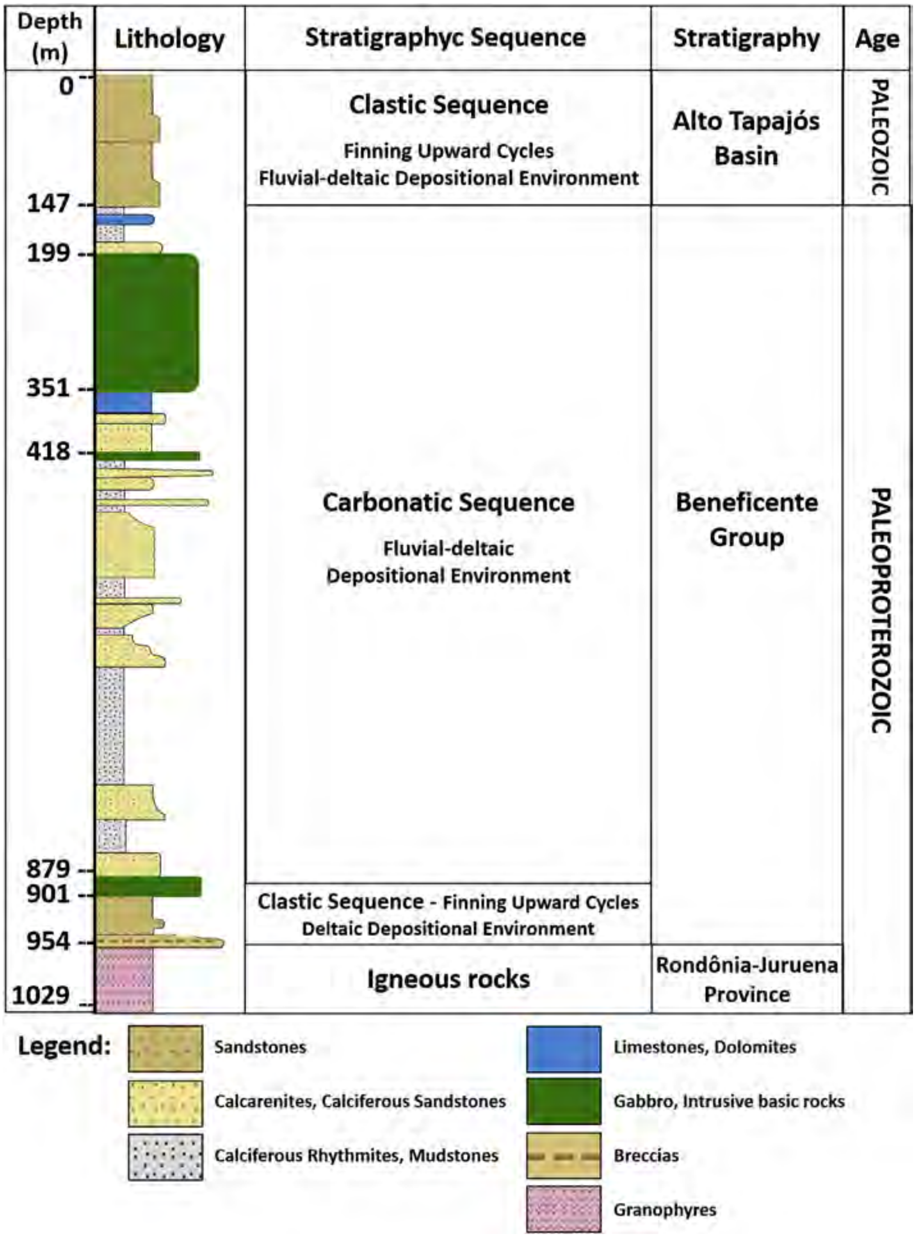

Fig. 5. Schematic lithostratigraphic column of the Cachimbo Well and tentative correlation with cratonic units exposed in adjacent areas to the Alto Tapajós Basin (Modified from Lopes, 2001).

institutions and sources, such as: (1) geological information made available by the Geological Survey of Brazil (CPRM), organized in geographic information systems and consolidated at Geological Map of Brazil 1:1.000.000 scale; (2) geological information from two fields campaigns; (3) data from aerogeophysical surveys made available in 2016 by the CPRM's Remote Sensing and Geophysics Division; (4) public domain Bouguer anomaly data obtained by the International Gravimetric Bureau (BGI), available at http://bgi.omp.obs-mip.fr/; and (5) digital terrane model (DTM) data, provided by the US Geological Survey Eros Data Center, 2005 version (public domain).

3.1. Structural analysis

3.1.1. Structural framework

The Alto Tapajós Basin units crop out in low altitude terrains in its central, northern and northwestern sectors, contrasting with its southern and eastern plateau (Fig. 7), limited by the Serra do Cachimbo escarpments (Fig. 8). The interpretation of topographic lineaments from digital terrain model data guides to identification of surface distribution patterns that indicate basin's compartmentation. While tracking such features, we considered lineaments with lengths between 50 and 100 km in the Alto Tapajós Basin area, and lineaments of 100–200 km in length in the surrounding cratonic regions (basement). The lineaments correspond to topographic features, ranging from escarpments and rectilinear ridges to elongated valleys and rivers (Fig. 7). Given the spatial orientation patterns recognized for the distinct groups of lineaments, associated to the observation of the different rosette diagrams related to them, the following compartmentalization was adopted covering all basin (Fig. 7):

1) Northwestern Compartment – Characterized by lineaments with a predominant N24E-S24W trend and a subordinate N-S trend (Fig. 7A).
2) Central-Southwestern Compartment – Characterized by lineaments with N33E-S33W main direction, mostly with a length of 100 km and associated with positive topographic features (Fig. 7A).

Fig. 6. Devonian Lower Carboniferous sedimentary rocks from the Alto Tapajós Basin: a) Cross bedded sandstones. b) Ripple marks in siltstones. c) Flat parallel-bedded to massive sandstones. d) Shales with siltstones interlayers. Late Carboniferous to Permian sedimentary rocks in the central region of the Alto Tapajós Basin: e) Layers of sandstones with cross bedded and parallel structures. f) Laminated rhythmites and associated concretions.

3) Central-Eastern Compartment – The lineaments present predominantly N49W-S49E orientation, mostly with an extension of 100 km. However, lineaments of 50 km with NE-SW and E-W strikes occur subordinately (Fig. 7A).
4) Basement of the Tapajós-Parima Province – Characterized by predominant N37W-S37E lineaments mainly with an extension of 200 km, which prevail in the area bordering the central-eastern compartment (Fig. 7B). In the region close to the central-southwestern compartment (2), lineaments with an extension of 100 and 200 km and NE-SW strike are identified.
5) Basement of the Rondônia-Juruena Province – Characterized by lineaments with N72W-S72E main direction, mostly with extension of 200 km (Fig. 7B). In a secondary way, lineaments with NE-SW orientation and extension of 100 km are recognized close to the central-southwestern compartment (2).

3.1.2. Structures – field observations

In the field, the existence of basement highs segmenting some areas of the Alto Tapajós Basin was confirmed by an outcrop with an unconformity between a mafic plutonic intrusion and sandstones (Fig. 8), along the road BR-163 (Fig. 4). At the Juruena River Valley, we visited a region with the contact between the Paleoproterozoic sedimentary sequence (basement) and the Permo-Carboniferous units of the Alto Tapajós basin. In both units the same trend of fault damaged zones was observed. Within the Beneficente Group, a major NE-SW subvertical fault zone was identified close to the banks of Juruena River, near to the limit with the Alto Tapajós Basin (Fig. 8). The same structural pattern is verified in fault damage zones within the Permo-Carboniferous sedimentary layers (compartment 2 from Fig. 7a). Few kinematic indicators, such as striae and steps, show a left-lateral movement associated to these NE-SW faults (Fig. 8).

3.2. Aeromagnetic data analysis

3.2.1. Data and methods

The identification of magnetic anomalies of an area is very helpful for geological mapping, due to the fact that its variations are a response to the presence of distinct lithologies. The magnetic data here used as an aid to the determination of the structural framework of the Alto Tapajós Basin comes from seven surveys carried out by the Brazilian Geological Survey (CPRM, 2009a, 2009b, 2010, 2013a, 2013b, 2013c, 2014) between 2009 and 2014. These surveys do not cover the entire Alto Tapajós Basin, they are concentrated in the northern and western sectors of the basin (Figs. 9–11).

Among the available magnetic data, those related to total magnetic field, reduced from International Geomagnetic Reference Field (IGRF), were analyzed. In a first step, data from distinct surveys were merged in the same grid. Subsequently, the value scales were homogenized for visualization of an integrated map (Fig. 9).

Later, the application of spatial resolution filters was performed for the integrated available data of the total magnetic field. In a first approach, the Analytical Signal Amplitude (ASA) filter was used, due to its property of highlighting rocky body's edges, especially in areas with shallow sources and significant remaining magnetization (Li, 2006). In a second approach, the integrated data were submitted to vertical derivative filter, whose function is to highlight shallow geological sources.

3.2.2. Magnetic maps and analysis

The total magnetic field map, reduced from IGRF, reveals a projection of the structural framework of the basement provinces of the Amazon Craton underneath the Alto Tapajós Basin. The highest anomalies in central-northwestern of the Alto Tapajós Basin and surrounding region of Tapajós-Parima Province are following a NE-SW

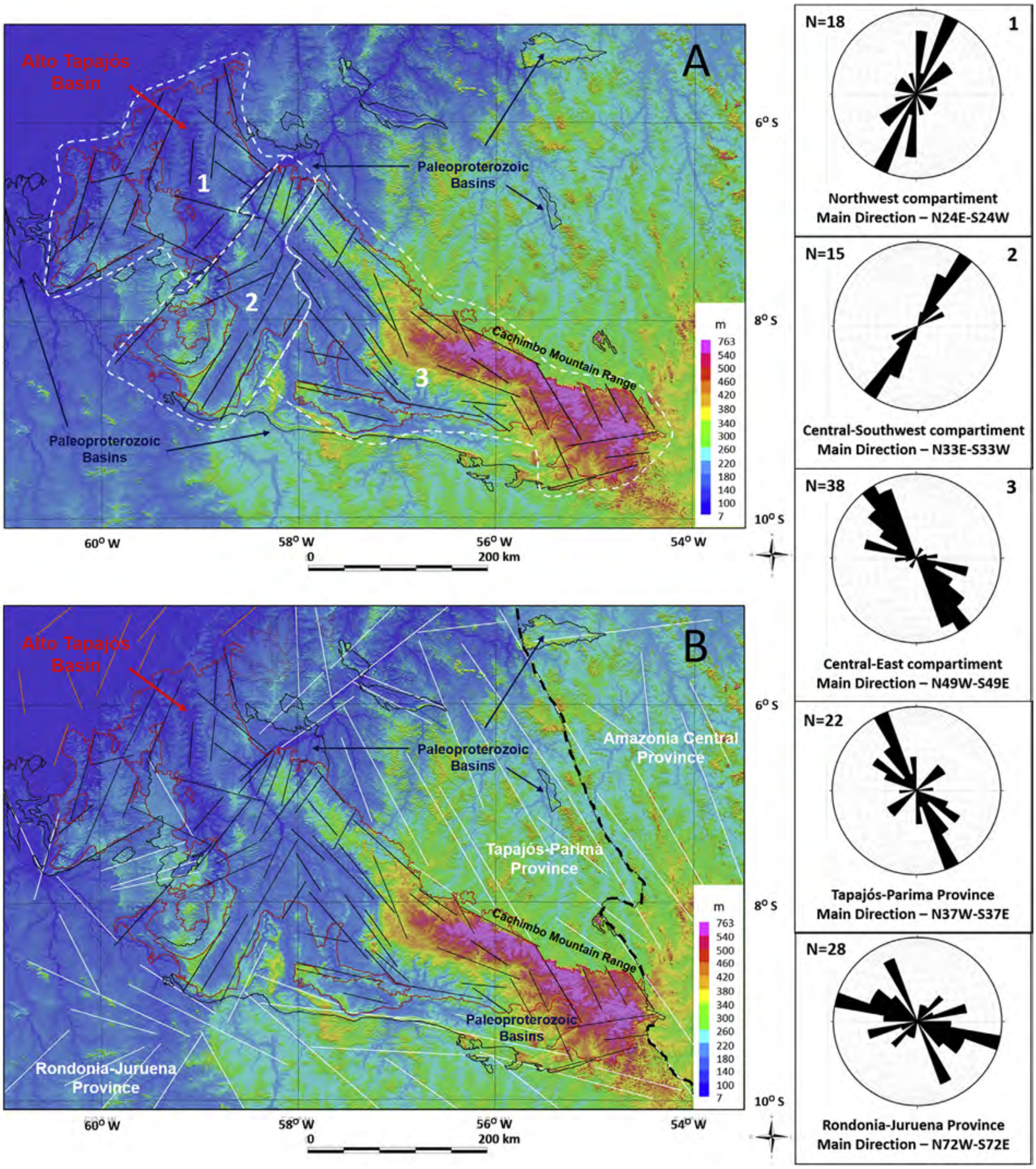

Fig. 7. Major topographic lineaments recognized on the digital model topography of the Alto Tapajós Basin and surrounding Amazon Craton Provinces. A) Structural compartmentation of the Alto Tapajós Basin (white dashed lines) set by its topographic lineaments pattern (black traces). B) Topographic lineaments recognized for the cratonic regions (white traces). Black dashed lines as boundaries between Amazon Craton Provinces. To the right, rosette diagrams depicting the predominant direction of the lineaments in the distinct compartments of the Alto Tapajós Basin and adjacent basement provinces (N = number of measured lineaments).

trend. This pattern shows a discrepancy concerning about the WNW-SSE trend of highest anomalies in Rondônia-Juruena Province, so a NW-SE boundary between two distinct magnetic domains can be inferred along the Alto Tapajós Basin (Fig. 9).

The analysis of the ASA map of the total magnetic field allowed the visualization of a magnetic domain formed by strong anomalies (Fig. 10), characterized as thin NNE-SSW magnetic lines extending hundreds of kilometers, concentrated in the central and southwestern regions of the basin (Fig. 10). These anomalies are concordant to the structural trend previously identified for the central-southwestern compartment (Fig. 7). It is also possible to note that these NNE-SSW lineaments cross cut NW-SE lineaments, generating an offset that indicates a dextral NNE-SSW transcurrent component in the center of the Alto Tapajós Basin (Fig. 10). Both sets of magnetic linear anomalies are also present within the basement.

For the vertical derivative map of total magnetic field, the similarity between observed anomalies in the central areas of the Alto Tapajós Basin and those observed in the areas covered by the Paleoproterozoic basins is striking. However, in some areas on the basin boundaries, especially the ones in the central-east compartment near to Tapajós-Parima Province, the anomalies under the Alto Tapajós Basin resemble those observed on adjacent igneous and metamorphic terranes

Fig. 8. a) Aerial view of Cachimbo Mountain Range (Serra do Cachimbo), in the southeastern limit of the Alto Tapajós Basin (Courtesy: FAB – Brazilian Air Force). The sedimentary layers correspond to the Devonian formations. b) An inner basin structural high is evidenced by the occurrence of a gabro outcrop with the unconformity separating it from the Paleozoic sandstones. (red arrow). c) At the Juruena River Valley, NNE-SSW fault zones in the central region of the Alto Tapajós Basin close to the basement. NNE-SSW damage zone in the Beneficente Group. d) Striae and steps showing a left-lateral strike-slip fault in the permo-carboniferous sequence of the Alto Tapajós Basin. e) NNE-SSW strike-slip fault and associated fractures. f) NNE-SSW damage zone in cliffs close to Tapajós River. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Fig. 11).

3.3. Gravimetric data analysis

3.3.1. Data and methods

The Bouguer Anomaly data used here comes from the Earth Gravitational Model 2008 (EGM 2008), which was designed from the integration of data from terrestrial, marine and satellital surveys (Pavlis et al., 2012), and acquired through the database of the International Gravimetric Bureau (BGI) website. The Bouguer anomaly calculation employed a density of 2.67 g/cm^3 in the quantification of the gravitational effect of the masses between the point of observation and the reference point. The arrangement of points is 2.5′, which corresponds to a spacing of approximately 4.6 km.

Great variations on values of gravimetric anomalies under the Alto Tapajós Basin indicates the existence of unknown geological structures of regional scale, however the delimitation of these structures demands the processing of Bouguer Anomaly data through the application of spatial resolution filters. The use of the Total Horizontal Gradient (THDR) filter is an alternative in this evaluation, once applied in gravimetric data, this filter highlights abrupt changes between geological contacts that vary laterally due to unequal densities, being steeper gradients indicative of such changes. In short, the THDR filter positions peaks of the anomalies very close to the edges of the bodies, with minimum values in their central part (Ferreira et al., 2013).

3.3.2. Gravimetry domains

The Bouguer Anomaly map presents values ranging from −92 mGal to 42 mGal, but in general the most negative ones are concentrated in the basement areas surrounding Alto Tapajós Basin, except for some areas southwest of the basin that show positive anomalies (Fig. 12). The anomalies, whether shallow or deep, tend to increase positively along a NW-SE trend in conformity with the structural trend identified for the central-eastern compartment (Fig. 7).

The gradients of the Bouguer Anomaly values are also similar to the main structural frame of the Alto Tapajós Basin, as bounded in the concentration of positive values following a trend NW-SE (Fig. 12). The continuity of this trend is more evident in the central-eastern compartment, featuring an eastern gravimetric domain. The interruption of the NW-SE trend, in turn, coincides with the central-southwestern and northeastern compartments, where remarkable high gradient values occur more scatteredly, setting a distinct western gravimetric domain.

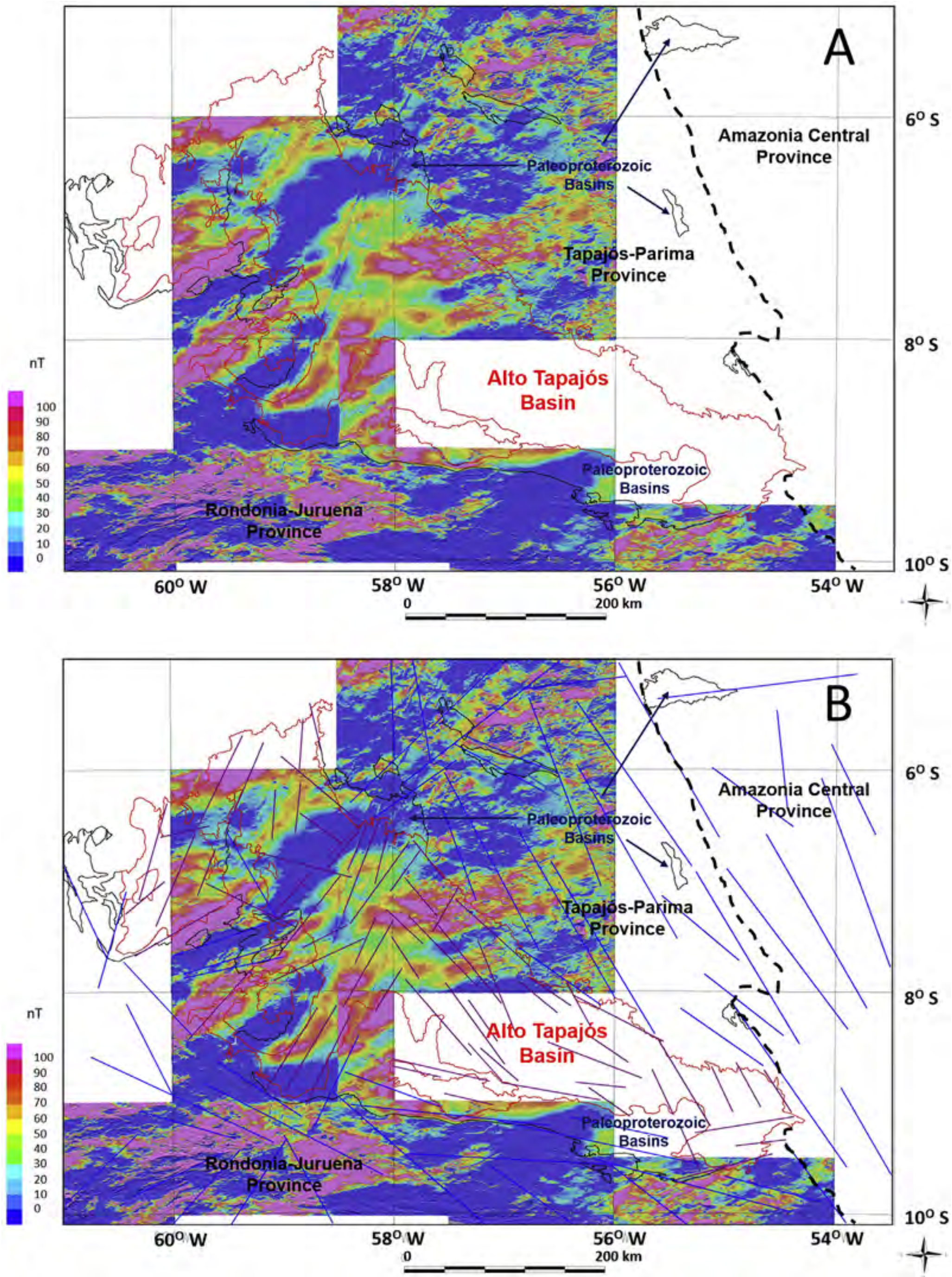

Fig. 9. A) Map of total magnetic field (reduced from IGRF) in coverage area of the Alto Tapajós Basin and surrounding Paleoproterozoic basement. Black dashed lines as boundaries between Amazon Craton Provinces. B) Distribution pattern of topographic lineaments, printed as blue and violet lines, confirm distinct magnetic domains on studied area. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

4.1. Data integration and interpretation

The integration of geophysical and topographic data with geological map information leads to the compartmentalization of the Alto Tapajós Basin into domains according its main geological structures and lithological contrasts (Fig. 13).

It is clear that the basin is limited and controlled mainly by orthogonal sets of brittle structures with trends NW-SE and NE-SW (Figs. 7 and 9), that coincide with dike swarms and also normal and oblique faults (Figs. 4 and 12B). The main axis of the basin is oriented NW-SE, parallel to the distribution of its sedimentary units. It also matches its basement boundaries, as the contact zone between the Beneficente Group and the Tapajós-Parima Province (Fig. 4), interpreted as zones of crustal weakness beneath the Alto Tapajós Basin. The Bouguer Anomaly map (Fig. 12A) also presents an anomaly that could be interpreted as crustal thinning under the central axis of the Alto Tapajós Basin, therefore the approximation of the Moho discontinuity, or the emplacement of high density rocky bodies (mafic units), on a regional scale.

The magnetic maps partially support this through the recognition of NNE-SSW mafic dike swarms in the basement north of the Alto Tapajós

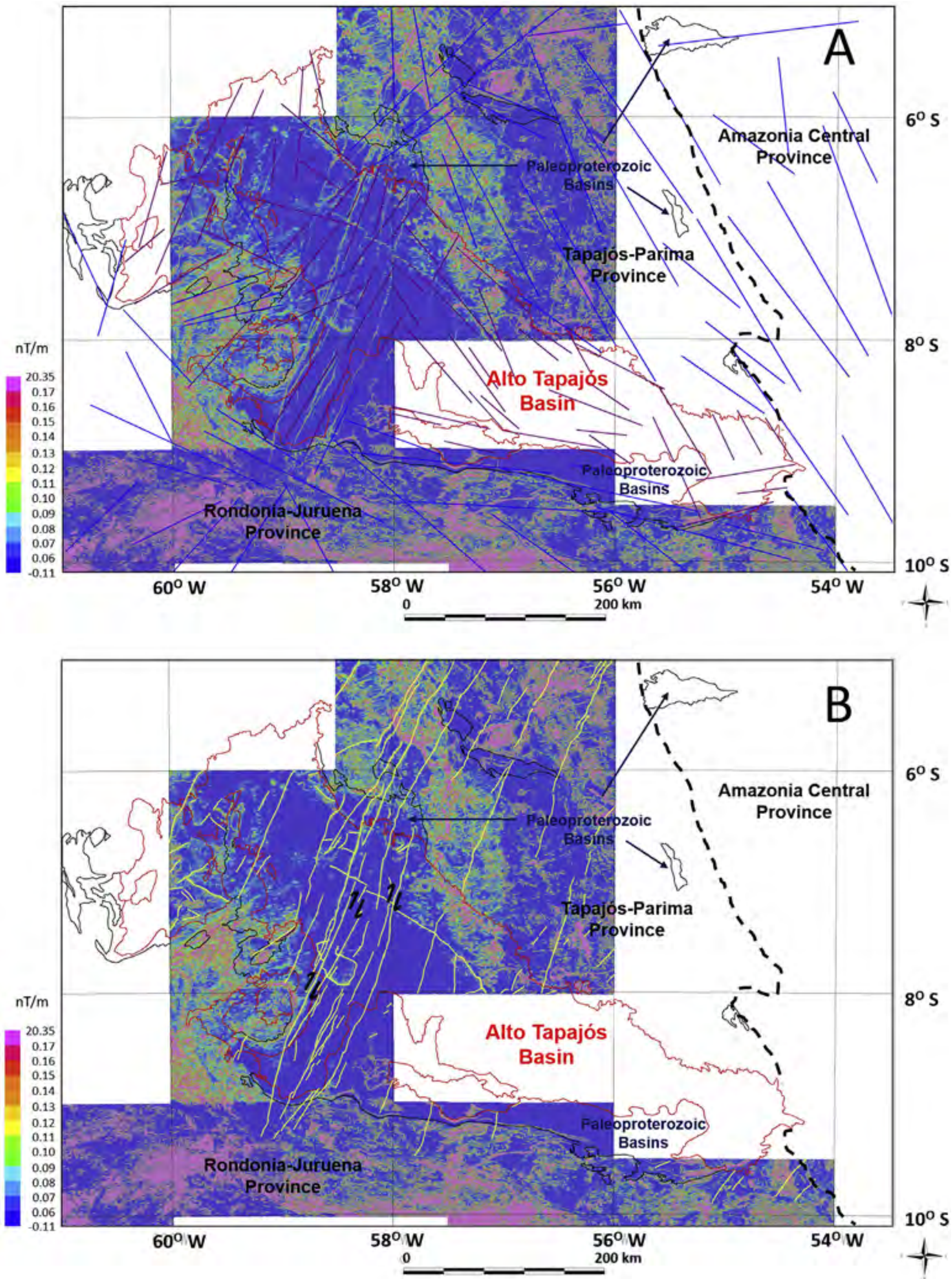

Fig. 10. A) Map of analytical signal amplitude of total magnetic field, reduced from IGRF, in coverage area of the Alto Tapajós Basin (red line) and surrounding Paleoproterozoic basement. Topographic lineaments represented as blue and violet lines. B) Magnetic lines (yellow) interpreted from map of analytical signal amplitude of total magnetic field reduced from IGRF and transfer faults interpreted (black arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Basin that are prolongated in the analytical signal amplitude map through the entire basin. This tectonic feature suggests an extensional set of fractures that might have also operated as faults with a dextral component, which segments older NW-SE structures (Figs. 10 and 13). For the areas where vertical derivative filter map showed predominantly high magnetic values (Fig. 11), due to the indication of shallow magnetic sources, the basin cover is interpreted as thinner, allowing the delimitation of inner structural highs (Fig. 13). Areas with predominant low magnetic values are perceived as having deep magnetic sources with higher Paleozoic and Proterozoic sedimentary thickness (Fig. 11).

4.2. Tectonic evolution of the Alto Tapajós Basin

The Alto Tapajós Basin NW-SE and NNE-SSW structural framework (Fig. 13) results from more than one tectonic event, also sustained by the tectonic history of the other Gondwana intracontinental basins since the Cambrian. Understanding its tectonic evolution requires an approach to the dynamic aspects of rifting, active or passive styles, in addition to the considerations about the basement inheritance. According to Merle (2011), active rifting is characterized by a crust uplift and abundant volcanism at an early stage, with formation of grabens and sedimentation at a later stage, resulting from a process of thermal erosion at the base of the lithosphere. On the other hand, passive rifting

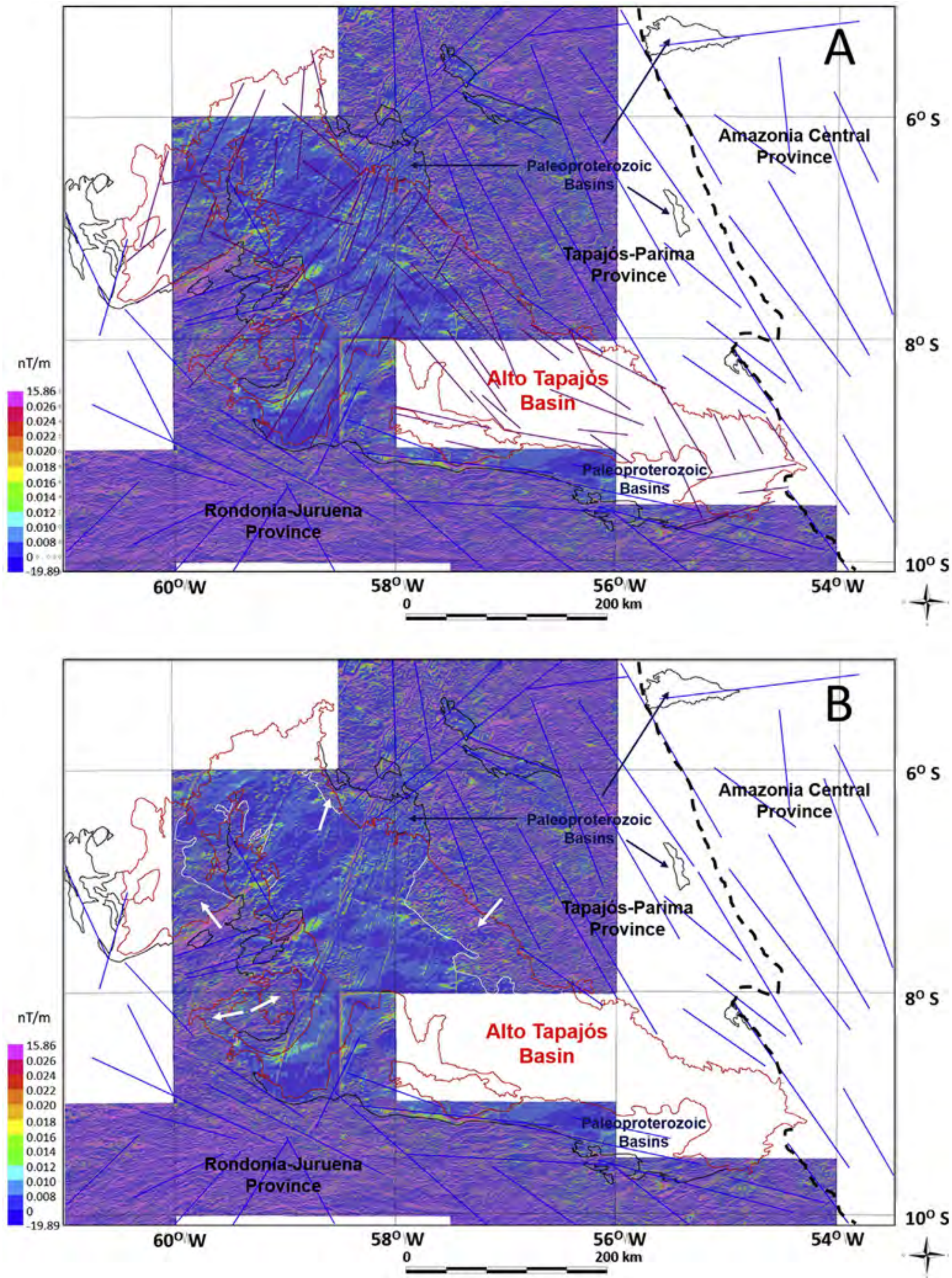

Fig. 11. A) Map of vertical derivative of total magnetic field in coverage area of the Alto Tapajós Basin and surrounding paleoproterozoic basement. Black and violet lineaments were delimited from topographic data (Fig. 7). B) Areas of the Alto Tapajós Basin in which contrasts of anomalies have visible compatibility with igneous/metamorphic Proterozoic terranes (basement), indicated by white arrows. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

exhibits formation of grabens and lacustrine or even marine sedimentation at an early stage, followed by volcanism at a final stage, resulting from the horizontal extension of the lithosphere.

The Alto Tapajós Basin features indicate that it formed from the evolution of a dominantly passive rift, due to the lack of abundant volcanism during the Paleozoic Era, predominance of fluvio-deltaic and marine facies and also proeminent structural control of the deposits. Considering its NW-SE depocenter during the Devonian and Lower Carboniferous and the absence of a connection with coeval formations in the Amazonas Basin (Fig. 2), it is inferred that during Middle Paleozoic the Alto Tapajós Basin was relatively isolated.

In a first preserved stage of subsidence, during the Devonian-Lower Carboniferous, crustal structures of the basement on the Tapajós-Parima Province might have controlled the sedimentation, considering the orientation of the formations and the direct basement contacts (Figs. 4 and 14). However, the overlapping of sediments beyond rift flanks, away from the tectonically extended areas and over wider areas, may be an evidence of a slow thermal subsidence aftermost initial rifting episodes (Teixell et al., 2009).

As for a second main episode of subsidence, some elements indicate a displacement of basin depocenter towards west, such as: deposition of Upper Carboniferous rocks on the Paleoproterozoic sedimentar Beneficente Group and the occurrence of Permian formations restricted to the basin's central region. A subordinated NE-SW deposition axis is

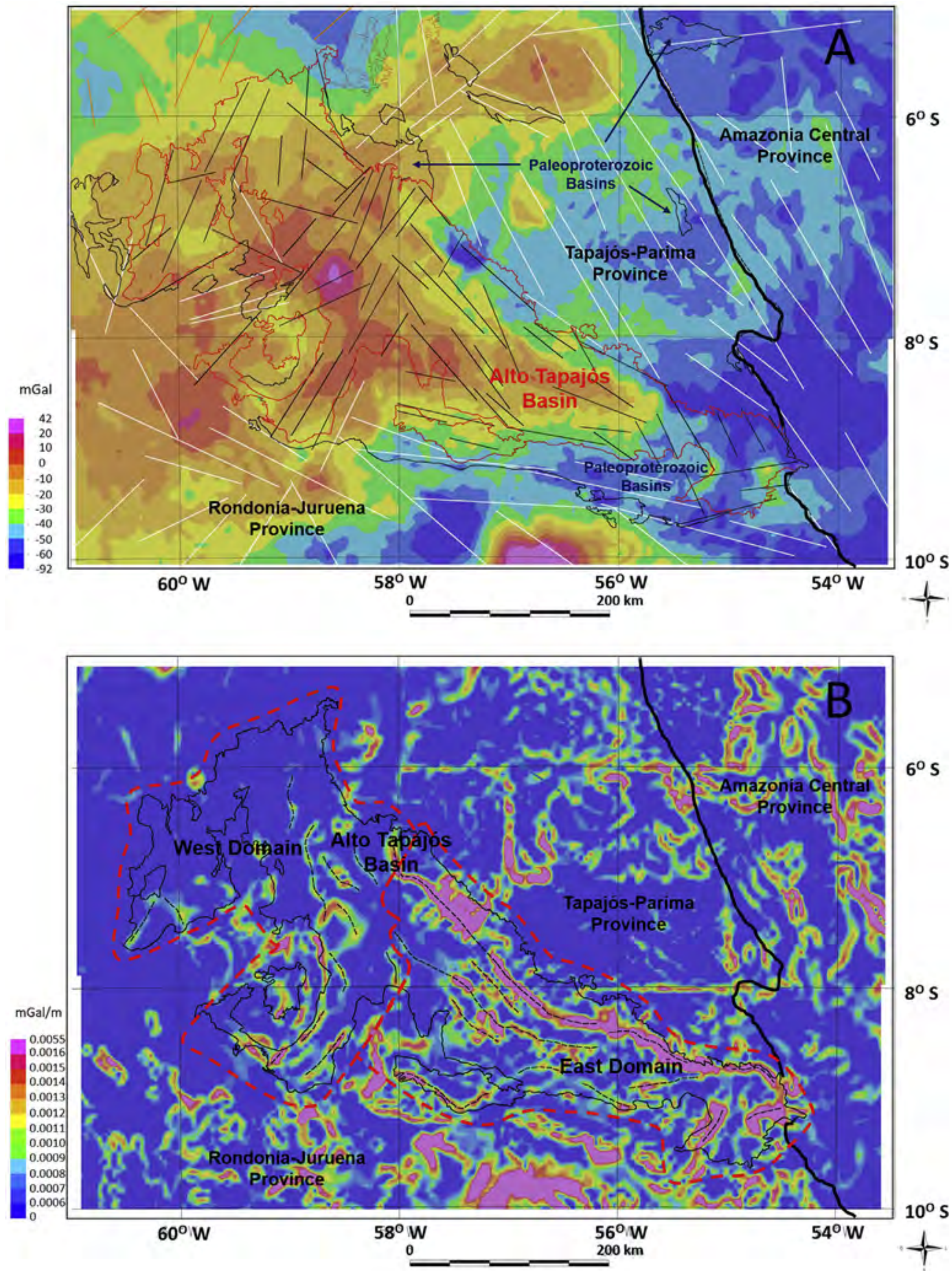

Fig. 12. A) Bouguer Anomaly map and topographic lineaments of the Alto Tapajós Basin (thin black lines) and surrounding Paleoproterozoic basement (thin white lines). B) Map of Total Horizontal Gradient Filter (THDR) applied to Bouguer Anomaly data. Red and thin black dashed lines refer to gravimetric domains boundaries and high gradients values trends, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

identified, basically corresponding to the central-southwestern basin compartment (Figs. 4 and 14).

McClay et al. (2002), in an analysis on the evolution of rifts based on analogical models and the observation of natural rifts, recognize different patterns of extensional breaking in these tectonic environments. In basins formed by orthogonal or moderately oblique extensional systems, the border faults are segmented parallel to the rift axis and the intra-rift faults are parallel to the extensional direction. However, the greater the stresses obliquity to the rift axis, the greater the segmentation of the rifted margin. In the case of basins formed by predominant oblique fault systems, they are characterized by highly segmented border faults and the formation of sub-basins along the rift zone. As for the arrangement of the inferred extension structures for the Alto Tapajós Basin, it is possible to verify a relative segmentation of the normal faults constituting the rift shoulders, while the intra-rift faults are subparallel to these borders (Fig. 15). This structural framework indicates that the fault system, associated to the Alto Tapajós Basin, was formed due to extension efforts moderately oblique to the main recognized rifting trends (Fig. 15).

4.3. Fossil rift and basement inheritance

The significance of ancient structures has been recognized for the formation of continental rift systems, affecting their location and

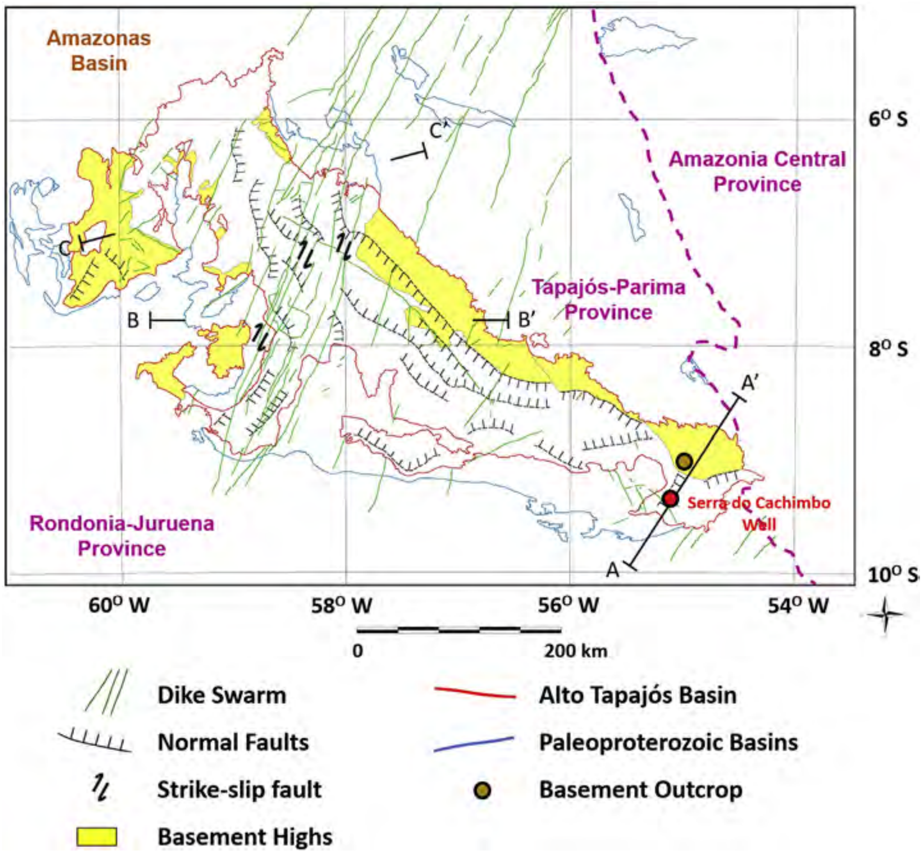

Fig. 13. Integration of the magnetic and gravimetric maps with the geology and structural grain of the Alto Tapajós Basin. Dike swarms are inferred from magnetic maps. Basement highs and normal faults are inferred from gravimetric data combined with geological information. Note that the actual limits of the Alto Tapajós Basin and the older Paleoproterozoic basins are shown, as well as the main provinces of the Amazon Craton. The location of the schematic geological sections from Fig. 14 correspond to A-A′, B-B′ and C-C′ tracings.

segmentation. The actual Afro-Arabian Rift System follows Proterozoic orogenic belts and shear zones, avoiding the older Archean nuclei as the Tanzanian Craton (Muirhead and Kattenhorn, 2018). These structures are repeatedly reactivated during different tectonic events (Chorowicz, 1989; Corti, 2009; Dawson et al., 2018). As ancient suture belts are major discontinuities not only in the crust, but in the whole lithosphere (Chorowicz, 1989), their main trend can be noticed in Bouguer Anomaly maps too, as it is also shown in Alto Tapajós Basin's basement NW-SE framework (Fig. 12).

The NW-SE fabric of the Alto Tapajós Basin coinciding with the underlying Paleoproterozoic sedimentary formations corroborates to the hypothesis that, during the Paleozoic, Precambrian extensional structures were reactivated. The predominant structural control of the basement units reinforces the hypothesis that the basin initiated as a passive rift, mostly an intracontinental basin. In addition, the large sedimentary thickness of the Paleoproterozoic Beneficente Group, at least 633 m according to the drill core (Fig. 5), confirms that this ancient basin followed this NW-SE orientation. In this case the Alto Tapajós Basin would have been developed in a fossil rift (Fig. 16).

As for the spatial disposition of the structural highs interpreted from the magnetic data in the Alto Tapajós Basin, there is a NE-SW gap matching the central-southwestern compartment (Fig. 11). At the northwestern and central-southwestern compartments, structural highs are concentrated nearer the Rondônia-Juruena Province, at the central-east compartment they occur along the border limited by the Tapajós-Parima Province (Fig. 13). The spread of these structural features in distinct edges implies an asymmetry of the rift, which might to indicate a dip inversion of its main faults. Chorowicz (1989) points out that many segments of rift basins are crossed by transfer faults with associated reversion, generally showing a high angle orientation relative to the length of the rift (Fig. 16). It is observed the extensional faults mostly abut against the NE-SW transfer fault recognized at the central-southwestern compartment (Figs. 13 and 16), while few ones merge tangentially to it. This arrangement between an oblique pre-existing structure and normal faults indicates an active fabric related to a constant reactivation of shear zones (Misra and Mukherjee, 2015).

Late Proterozoic crustal stretching and Early Paleozoic extensional reactivation of Precambrian structures are commonly proposed to elucidate the initial subsidence mechanism for Western Gondwana Paleozoic intracratonic basins of South America (Milani and Zalán, 1999) and Africa (Kadima Kabongo et al., 2011). Such hypothesys is considered for the Alto Tapajós Basin too, as Cambrian and Ediacaran mafic dykes are present on its bordering basement (Santos et al., 1999; Tassinari, 1996). However, continental rifting is not just related to mechanisms associated to lithospheric thinning. Secondary ones, as upwelling of the asthenosphere and heating of the lithosphere, occur before and during rifting (Olsen and Morgan, 2006). These processes result in generation of remarkable volumes of mantle derived-magmas which are incorporated to the crust. Such features also could be inferred for Alto Tapajós Basin, based on sharply NW-SE regional anomalies printed on gravity maps (Fig. 12). The same interpretation is accounted for other fossil rifts, like U. S. Midcontinent Rift System (Olsen and Morgan, 2006). It is marked by a geophysical signature of intense and well-defined regional gravity anomalies, which are caused by massive volumes of extrusive mafic rocks. Though there are no lava flows or major magmatic province outcropping in the Alto Tapajós Basin.

4.4. *Western Gondwana Paleozoic tectonic evolution*

Correlation between the evolution of the Alto Tapajós Basin and tectonic events of Western Gondwana can be established. The formation and evolution of the Alto Tapajós Basin may be associated with the propagation of stresses in an intraplate environment during the Terra Australis and Alleghanian orogenies, in the Early and Late Paleozoic respectively (Fig. 17). Its structural framework (Fig. 13) is oblique to these orogens, making this feature susceptible to reactivation and

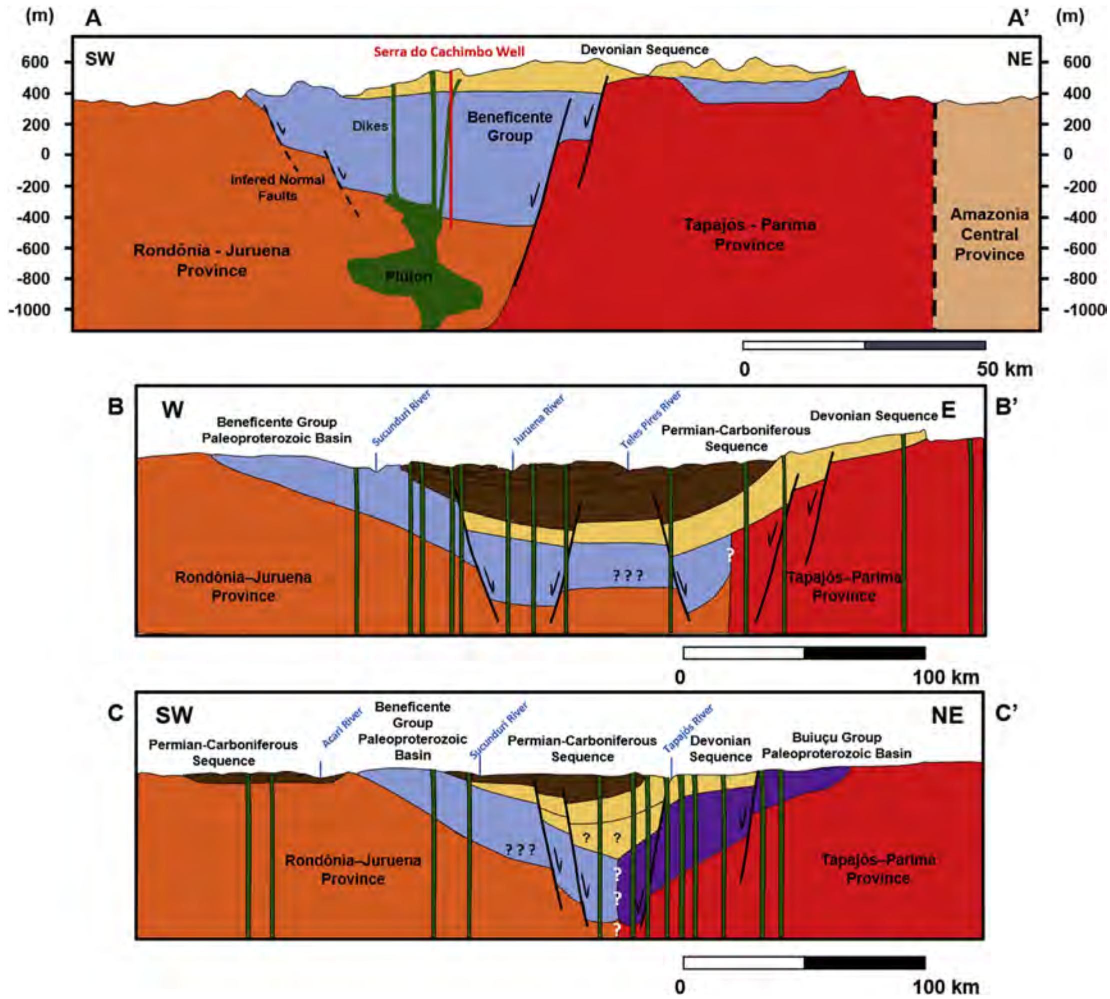

Fig. 14. Schematic geological sections A-A′, B-B′ and C-C′, all localized in Fig. 13. Note that the A-A′ geological cross section shows only the Devonian-Lower Carboniferous sequence at central-eastern compartment, in contrast to sections B-B′ and C-C′ depicting the Permo-Carboniferous sequence in the central portion of the Alto Tapajós Basin. Geological sections B-B′ and C-C′ have a vertical exaggeration of 9 times.

rifting (Fig. 17).

The initiation of rifting in the Alto Tapajós Basin is estimated as occurred in the period between the end of Proterozoic and the Lower Cambrian. At this time, Western Gondwana was passing through the transition between a stage of instability, characterized by the Brasiliano-Pan African orogenies that consolidated several continental plates into one major continent, to a stage of stability, marked by the development of platform covers since the Ordovician (Almeida et al., 2000; Brito Neves, 2002). In the south-central region of Amazonia, a region not affected by the Brasiliano tectonic events, intrusion of Ediacaran and Cambrian mafic dikes swarms took place (Tassinari, 1996; Santos et al., 1999) in the Alto Tapajós Basin adjacent basement. On the other hand, sedimentation started only in the Devonian, according to the outcropping record. Unfortunately, there is no seismic data from the Alto Tapajós Basin that could point out the existence of older rifting sedimentary strata pre-Devonian.

Similar ages are recognized in mafic dikes from intracratonic basins in North America (Klein and Hsui, 1987), which are attributed to a large process of crust deformation associated to the breakup of a Late Precambrian supercontinent, Pannotia. The sequel of rifting events, that separated North America block from the recently formed Gondwana, might have triggered the pre-Andean orogenies, which had a direct influence on the configuration of the Brazilian intracratonic basins in the context of their Paleozoic evolution (Zalán, 1991). Among such orogens, the Terra Australis and the Alleghanian have expressive proximity to the Amazon Craton. Regardless of there is no general comprehension upon the intraplate tectonics related to far-field stresses propagating from convergent plate-margins, the style of intraplate deformation can include an extension dominated tectonic regime (Aitken et al., 2013).

The Terra Australis Orogen, which encompasses thrust and fold belts extending throughout the Gondwana Southern margin, from the actual Andes to Northeastern Australia, developed between the end of Neoproterozoic and the Early Triassic (Fig. 17 - Cawood, 2005). These authors indicate episodic extensional events characterized by the formation of basins above suture zones, predominantly reactivation zones. Ramos (2010), in a Lower Paleozoic reconstruction, describes multiple collisions of continental blocks along a NW-SE trend against the Amazon Craton in regions geographically close to the Alto Tapajós Basin (Fig. 17). The sedimentation axis of the basin at this time was NW-SE, parallel to the Gondwana margin orogens (axis A from Fig. 17).

In the Upper Paleozoic, the Alleghanian Orogeny corresponds to an oblique collision among Laurentia and Gondwana during the formation of Pangea (Neves, 2011; Torsvik and Cocks, 2013; Domeier and Torsvik, 2014). Ramos (2010), while depicting the southern segment of Alleghanian Orogeny, represents it as a NE-SW deformation zone (Fig. 17), related to collision of continental fragments from Laurentia against proto-South America (Stampfli et al., 2013). In the Alto Tapajós Basin there is a shift on the axis of sedimentation, from NW-SE to NNE-SSW (axis B from Fig. 17), the latter parallel to the Alleghanian Orogen.

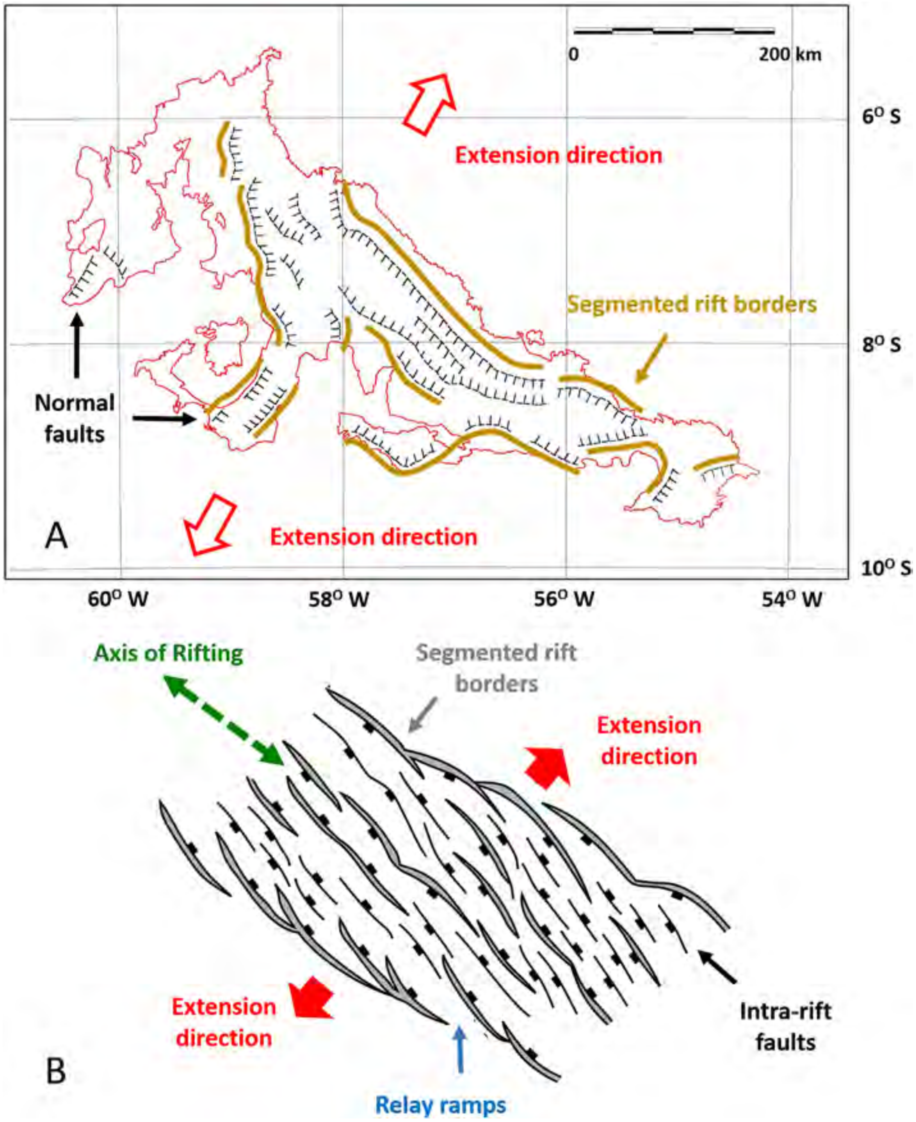

Fig. 15. Analogy between (A) the arrangement of normal faults inferred in the Alto Tapajós Basin and (B) conceptual pattern diagram of extensional breaking in moderately oblique rift systems (Adapted from McClay et al., 2002).

The period of transition between the Terra Australis and the Alleghanian orogenies marks a shift on the orientation of stresses on the crust which might be related to the framework evolution of the Alto Tapajós Basin. The unconformity between the Devonian-Lower Carboniferous and Permian-Upper Carboniferous sequences is one of the features that correspond to this transition period. Geological Map of Brazil 1:1M scale (CPRM, 2004) shows Ipixuna Formation overlapping directly the Borrachudo Formation and the basement (Fig. 4). Given the numerous aspects that shaped Alto Tapajós Basin tectonic evolution, these are presented in synthesis under proposal of a simplified stratigraphic chart (Fig. 18).

Synchronous to Alto Tapajós Basin, the cratonic subsidence was very pronounced at Paraná, Amazonas e Parnaíba basins during Devonian and Eocarboniferous (Soares et al., 1978; Milani et al., 2007). While during Carboniferous and Permian, there was an interruption in the subsidence process, followed by the development of uplift zones (Geraldes et al., 2015) and widespread erosion (Soares et al., 1978; Milani et al., 2007).

4.5. Mesozoic and cenozoic evolution

The occurrence of Jurassic NNE-SSW mafic dike swarms cross cutting the main sequences of the Alto Tapajós Basin marks the end of the Alleghanides Orogen and subsequent Pangea break-up. Ages between 180 and 220 million of years recognized for Cachimbo Range dikes (Lima and Bezerra, 1991 - K-Ar method), correlating these rocks with the Central Atlantic Magmatic Province (CAMP).

The CAMP corresponds to the largest sequence of continental flood basalts on the planet, consisting of tholeitic basalts and mafic intrusions extending over 7 million km^2 (Marzoli et al., 1999). Although widely eroded, it is preserved in an area that runs from Greenland and Western Europe, through North Africa and Southeast North America, with large remnants in South America and West Africa (Whiteside et al., 2007). The CAMP thus includes circa 2.5 million km^2 of widespread magmatism in central and northern Brazil (Marzoli et al., 1999), encompassing Alto Tapajós Basin and contiguous regions (Fig. 19). At an age established in 201 million years, the CAMP had its activity developed in equatorial and subtropical latitudes along the supercontinent Pangea (Svensen et al., 2017). In the same way as other igneous provinces, this event influenced an important rearrangement of tectonic plates, culminating with the opening of the central part of the Atlantic Ocean. An expressive fact is that an important portion of the CAMP, in terms of volumes, consists of products housed in Brazilian sedimentary basins (Svensen et al., 2017), reinforcing the possibility of connecting this

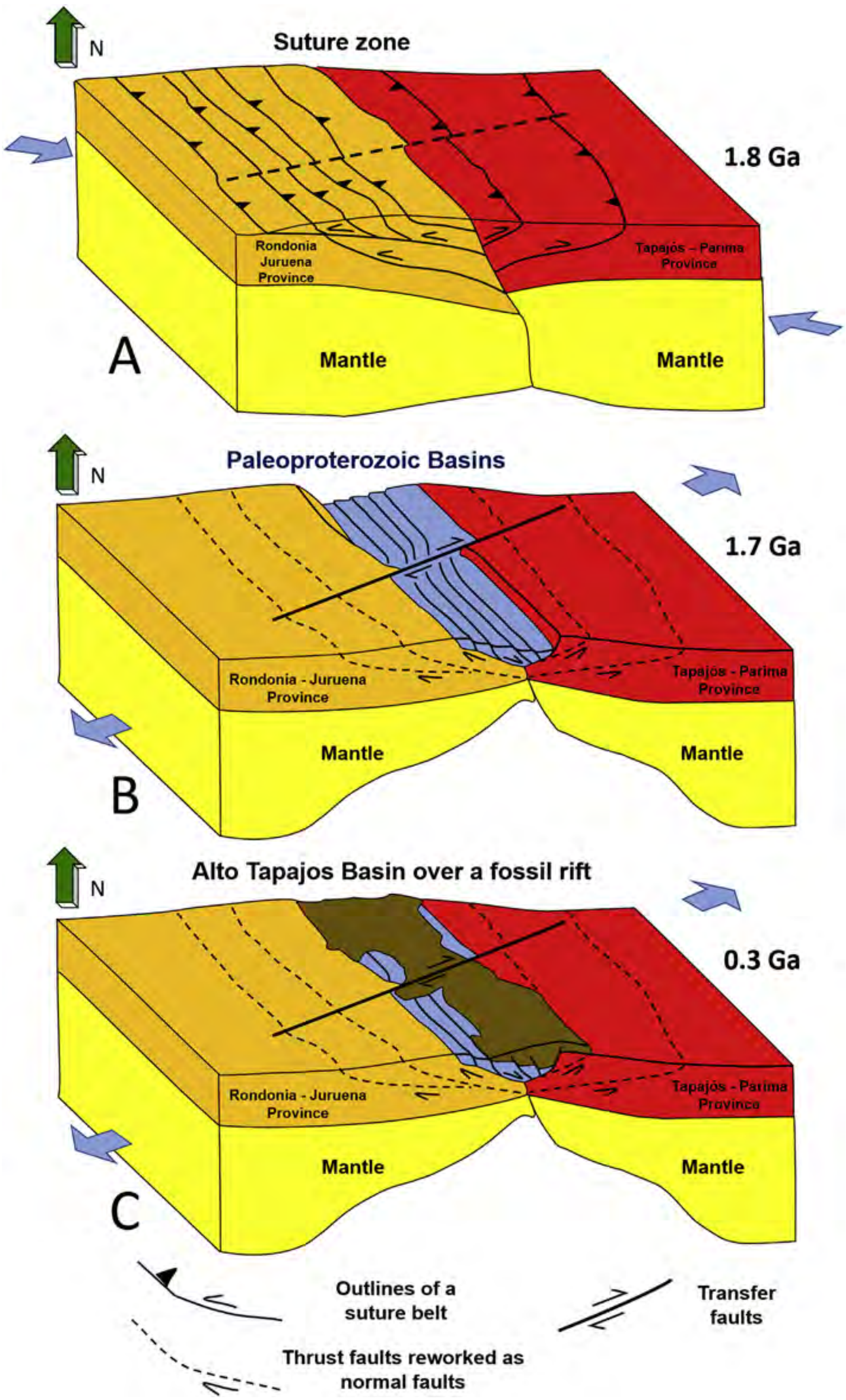

Fig. 16. Block diagrams showing the tectonic evolution of the Alto Tapajós Basin region, from the Paleoproterozoic until the Permian, suggesting the existence of a fossil rift correlating a suture zone with the formation of at least two basins (Figure adapted from Chorowicz, 1989). A) Inferred outlines of a suture zone produced due to the convergence between Rondônia-Juruena e Tapajós-Parima blocks. B) Reactivation of the thrust faults in an extensional environment right after the collision, forming the rift in which Beneficente and Buiuçu groups deposited. C) Reactivation of normal and transfer faults during Paleozoic due to crustal stretching, allowing the sedimentation of the Alto Tapajós Basin.

event to the formation of NNE-SSW oriented dike swarm of the Alto Tapajós Basin (Figs. 13 and 19). The CAMP thick intrusions provoked the uplifting of the Paleozoic formations of the Alto Tapajós and Amazonas basins, being such process more significant in the regions of Gurupá and Purus arches (Fig. 2a), and a larger relative subsidence in the center of the Amazonas Basin, due to the weight exerted on this area by the wider sill thickness (Caputo and Soares, 2016).

The localized Jurassic dyke swarm reusing the inferred NNE-SSW transfer zone of the Alto Tapajós Basin at its central-southwestern compartment, linked to an inherited basement fabric, lead to the interpretation that such structures were activated through a complex interplay among the development of CAMP event and the tectonic features of the continental rift associated to Alto Tapajós Basin. Such hypothesis, regarding the activation of preexisting transverse structures during a magmatic event, is recognized in other regions of the former Western Gondwana, like in the East African Rift System (Muirhead and Kattenhorn, 2018).

The absence of Cretaceous and Cenozoic formations on the Alto Tapajós Basin can be related to a long-term history of uplift and crustal stability that comprised the southern portion of the Amazon Craton.

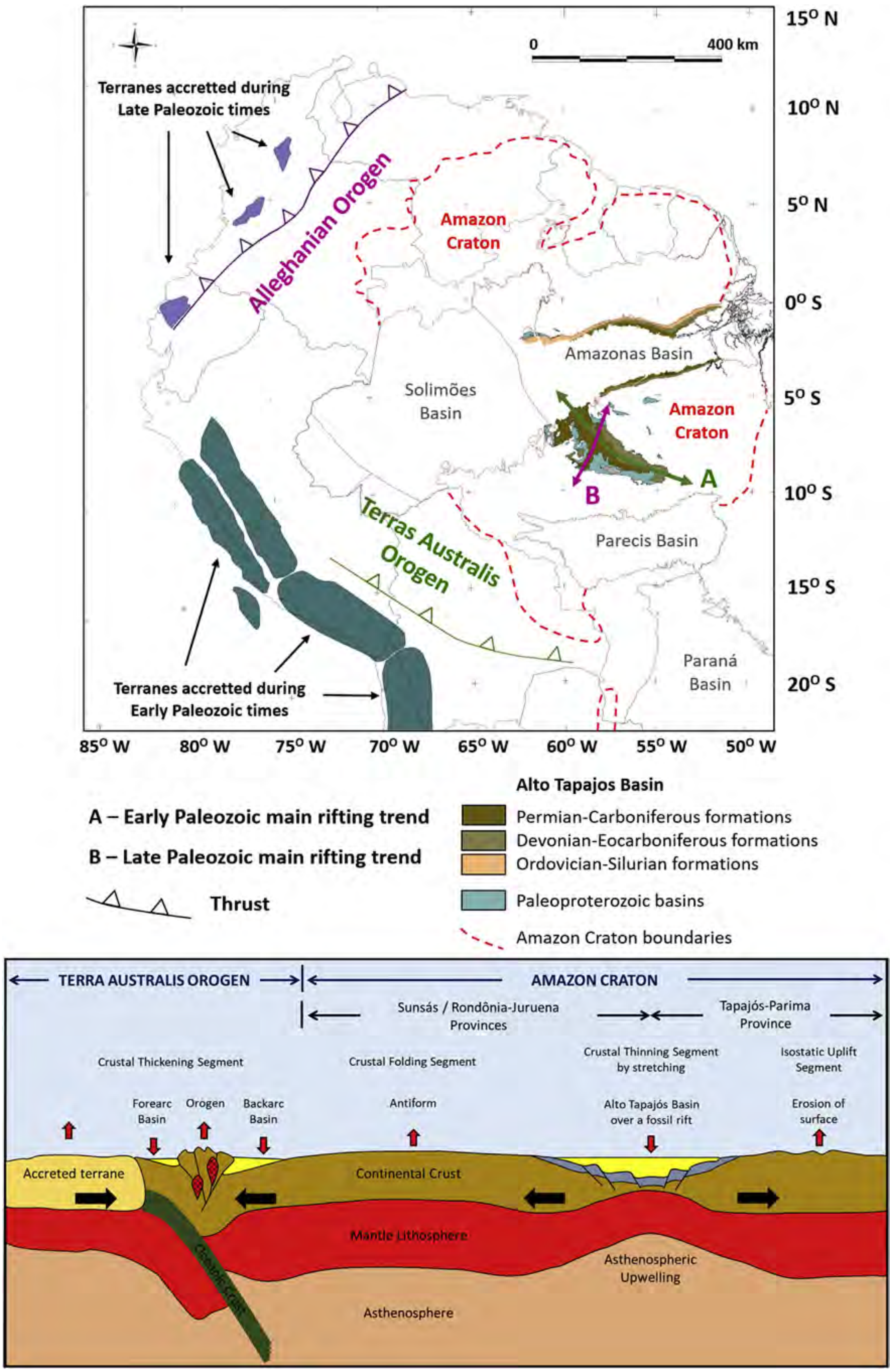

Fig. 17. Paleozoic orogenies of Gondwana western margin, modified from Ramos (2010), and their spatial connection to the main rifting axes of the Alto Tapajós Basin, which is depicted as a Paleozoic intracratonic basin over a Paleoproterozoic fossil rift. Schematic tectonic cartoon showing mechanisms of subsidence and crustal thinning in Amazon Craton associated with Terra Australis Orogen, in the Lower Paleozoic.

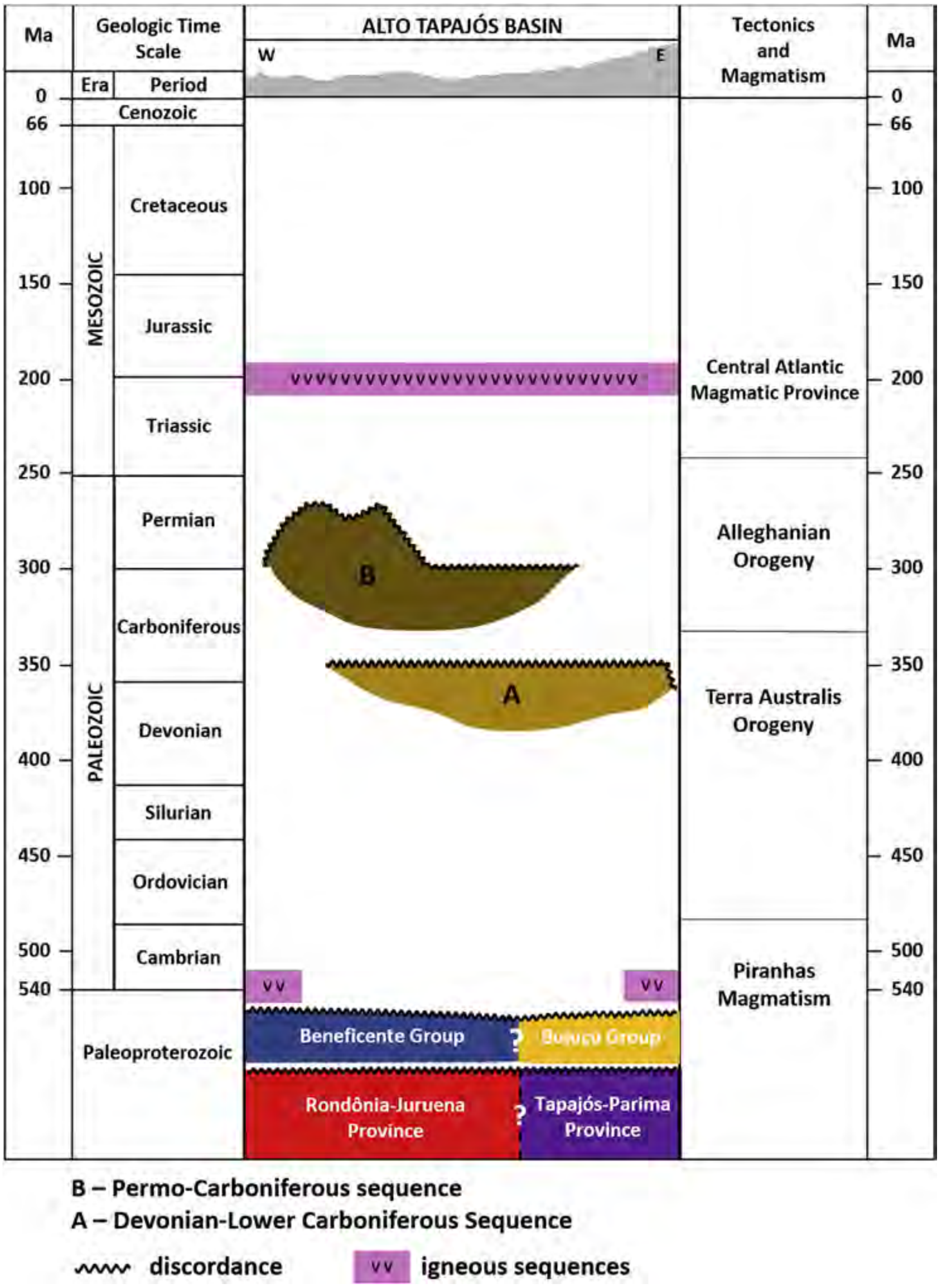

Fig. 18. Simplified stratigraphic chart of the Alto Tapajós Basin, highlighting the tectonic and magmatic events associated to deposition and erosion of recognized depositional sequences.

Episodes of accelerated denudation in this region, proposed by Harman et al. (1998), are coeval with the initial stages of Pangea breakup and postdated intraplate deformation related to South American Plate motion. Meanwhile a continuous increase in lithospheric buoyancy since the Late Cretaceous and Early Cenozoic periods, associated to plume–lithosphere interaction processes, has driven to the stabilization of the Amazon Craton (Hu et al., 2018), culminating in its present-day high topography. Specifically in the Alto Tapajós region, the proeminent Cachimbo Range and plateau register an uplift event that might explain the absence of thick Cenozoic deposits in comparison with the Amazonas Basin (Fig. 7).

5. Conclusion

The intracratonic Paleozoic Alto Tapajós Basin presents different phases of evolution related to reactivation of structures of a NW-SE Paleoproterozoic fossil rift within the Amazon Craton. The basement inheritance factor is here observed in geological, gravimetric, magnetometric and topographic data. In summary, the analysis of this data range allowed the recognition of normal faults, internal highs and a NNE-SSW large mafic dike swarm, characterizing in a simplified way the tectonic framework of the Alto Tapajós Basin.

The formation of the Alto Tapajós Basin dates back to a rifting process, associated to disintegration of a supercontinent (Pannotia) and formation of a new one (Gondwana) at the end of Proterozoic and Early Cambrian, characterized by basic igneous rocks of same age in the surrounding basement. However, the subsidence process that culminated with the evolution of the Alto Tapajós Basin as a depocenter individualized from the Amazonas Basin, is the result of crustal stretching developed between the Devonian and the Permian. These sedimentary

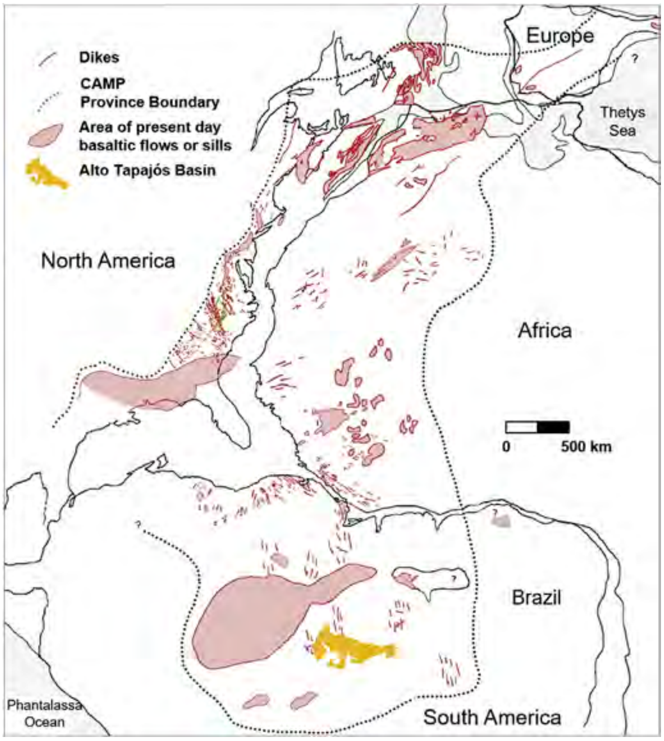

Fig. 19. Distribution area of the Jurassic-Cretaceous Central Atlantic Magmatic Province and depiction of the Alto Tapajós Basin in the central region of Pangea Supercontinent. Adapted from Whiteside et al. (2007). The Alto Tapajós Basin is highlighted in yellow. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

strata deposited on reactivation zones related to NW-SE normal faults and NNE-SSW oblique faults. The former is parallel, and some places coincident, with a major tectonic Paleoproterozoic crustal boundary that separates the Tapajós-Parima and Rondônia-Juruena geochronological provinces. The NNE-SSW oblique faults are interpreted as representing a transfer zone that accommodates the Paleozoic oblique rifting mode.

The relative apartness of the Alto Tapajós Basin is suggested by spatial distribution of Paleozoic formations isopachs of the Amazonas Basin, which tend to disappear toward the Purus Arch region and Alto Tapajós Basin bordering area. Among the main distension mechanisms associated to subsidence, intraplate passive rifting is probably the best explanation, in response to tectonic events that had occurred in Western Gondwana margins, corresponding to Terra Australis and Alleghanian orogenies.

The shift on the depocenter axis of the basin, from NW-SE to NNE-SSW, might be related to the change on orientation of stresses due to these two orogenies. This corroborates with the presumption that the far field stresses controlled most of the evolution of this intracratonic basin, and the so-called passive rift mechanism predominantes in its evolution.

In the Jurassic, Alto Tapajós Basin was submitted to a post-sedimentation tectono-thermal event, related to the disintegration of Pangea and expansion of the Magmatic Province of the Central Atlantic (CAMP). During this episode, 180–220 Ma mafic dike swarms intruded the central-southwest compartment, suggesting an avail of NNE-SSW structures previously reactivated in the Alleghanian Orogeny.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jsames.2019.102225.

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