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INVITED REVIEW

# Paleomagnetism of the Amazonian Craton and its role in paleocontinents

## *Paleomagnetismo do Cráton Amazônico e sua participação em paleocontinentes*

**Manoel Souza D'Agrella-Filho[1]*, Franklin Bispo-Santos[1], Ricardo Ivan Ferreira Trindade[1], Paul Yves Jean Antonio[1,2]**

**ABSTRACT:** In the last decade, the participation of the Amazonian Craton on Precambrian supercontinents has been clarified thanks to a wealth of new paleomagnetic data. Paleo to Mesoproterozoic paleomagnetic data favored that the Amazonian Craton joined the Columbia supercontinent at 1780 Ma ago, in a scenario that resembled the South AMerica and BAltica (SAMBA) configuration. Then, the mismatch of paleomagnetic poles within the Craton implied that either dextral transcurrent movements occurred between Guiana and Brazil-Central Shield after 1400 Ma or internal rotation movements of the Amazonia-West African block took place between 1780 and 1400 Ma. The presently available late-Mesoproterozoic paleomagnetic data are compatible with two different scenarios for the Amazonian Craton in the Rodinia supercontinent. The first one involves an oblique collision of the Amazonian Craton with Laurentia at 1200 Ma ago, starting at the present-day Texas location, followed by transcurrent movements, until the final collision of the Amazonian Craton with Baltica at ca. 1000 Ma. The second one requires drifting of the Amazonian Craton and Baltica away from the other components of Columbia after 1260 Ma, followed by clockwise rotation and collision of these blocks with Laurentia along Grenvillian Belt at 1000 Ma. Finally, although the time Amazonian Craton collided with the Central African block is yet very disputed, the few late Neoproterozoic/Cambrian paleomagnetic poles available for the Amazonian Craton, Laurentia and other West Gondwana blocks suggest that the Clymene Ocean separating these blocks has only closed at late Ediacaran to Cambrian times, after the Amazonian Craton rifted apart from Laurentia at ca. 570 Ma.

**KEYWORDS:** Amazonian Craton; paleomagnetism; supercontinents; Columbia; Rodinia; Gondwana.

**RESUMO:** *Dados paleomagnéticos obtidos para o Cráton Amazônico nos últimos anos têm contribuído significativamente para elucidar a participação desta unidade cratônica na paleogeografia dos supercontinentes pré-cambrianos. Dados paleomagnéticos do Paleo-Mesoproterozoico favoreceram a inserção do Cráton Amazônico no supercontinente Columbia há 1780 Ma, em um cenário que se assemelhava à configuração "South AMerica and BAltica" (SAMBA). Estes mesmos dados também sugerem a ocorrência de movimentos transcorrentes dextrais entre os Escudos das Guianas e do Brasil-Central após 1400 Ma, ou que movimentos de rotação do bloco Amazônia-Oeste África ocorreram dentro do Columbia entre 1780 e 1400 Ma. Os dados paleomagnéticos atualmente disponíveis do final do Mesoproterozoico são compatíveis com dois cenários diferentes para a Amazônia no supercontinente Rodínia. O primeiro cenário envolve uma colisão oblíqua da Amazônia com a Laurentia, começando no Texas há 1200 Ma, seguida por movimentos transcorrentes até o final da colisão da Amazônia com a Báltica há 1000 Ma. No segundo cenário, a ruptura da Amazônia e da Báltica do Columbia ocorre após 1260 Ma e é seguida por uma rotação horária e pela colisão desses blocos com a Laurentia ao longo do cinturão Grenville há 1000 Ma. Finalmente, a época em que a Amazônia colidiu com a parte central do Gondwana tem sido objeto de muita disputa. Todavia, os poucos polos paleomagnéticos do final do Neoproterozoico/Cambriano para o Cráton Amazônico, para a Laurentia e outros blocos do Gondwana Ocidental sugerem que o Oceano Clymene que separou estes blocos ocorreu entre o final dos períodos Ediacarano e Cambriano, após a separação do Cráton Amazônico da Laurentia há 570 Ma.*

**PALAVRAS-CHAVE:** *Cráton Amazônico; paleomagnetismo; supercontinentes; Columbia; Rodínia; Gondwana.*

[1]Departamento de Geofísica, Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo (USP). E-mails: *dagrella@iag.usp.br, frankb@iag.usp.br, rtrindad@iag.usp.br*

[2]Géosciences Environnement Toulouse (GET), Université de Toulouse, Observatoire Midi-Pyrénées, Toulouse, France. E-mail: *paul@iag.usp.br*

*Corresponding author.

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## INTRODUCTION

The paleogeography of continental blocks is the key piece of information to understand the geological evolution of our planet and the mechanisms that prevailed in the assembly and rupture of supercontinents, a process known as supercontinental cycle (Condie 2002). Based on the Pangea assembly, Meert (2012) defined that a supercontinent must comprise at least 75% of the existing continental crust. Based on this definition, the continental masses were united in supercontinents at least three times in Earth's history: 200 Ma (Pangea), 1100-1000 Ma (Rodinia), and 1850-1800 Ma (Columbia/NUNA). Note that large continental masses such as Gondwana and Laurasia did not comprise 75% of the continental surface, and therefore cannot be regarded supercontinents according to Meert's definition. The ages of assembly for the three supercontinents imply a periodicity of approximately 750 Ma for the supercontinent cycle (Meert 2012).

If we consider the peaks in U-Pb zircon ages, integrated with Nd isotopic ratios obtained for rocks all over the globe, we can assume the existence of a fourth supercontinent at ca. 2700 Ma (Hawkesworth *et al.* 2010). However, the reconstruction of such Archean supercontinent is a challenge given the scarcity of paleomagnetically viable targets of that age (Evans 2013). Some attempts to correlate Archean units based on geological and paleomagnetic data have been published, such as the formation of Zingarn supercraton made by the link of Zimbabwe/Rhodesia (Africa) and Yilgarn (Australia) blocks (Smirnov *et al.* 2013), or the Vaalbara supercraton formed by Kaapvaal (Africa) and Pilbara (Australia) blocks (de Kock *et al.* 2009). However, the lack of the main paleomagnetic poles for the Archean nuclei make paleogeographic reconstructions for those times very speculative (Buchan *et al.* 2000, Pesonen *et al.* 2003).

Several paleogeographic reconstructions of a Paleoproterozoic supercontinent (1850-1800 Ma) have been proposed in literature (e.g. Rogers 1996, Rogers & Santosh 2002, Zhao *et al.* 2002, 2003, 2004, 2006, Meert 2002, Pesonen *et al.* 2003, Hou *et al.* 2008a, 2008b, Johansson 2009, 2014, Yakubchuck 2010, Piper 2010, Evans & Mitchell 2011, Zhang *et al.* 2012, among others). This supercontinent has received different names: NENA (Gower *et al.* 1990), NUNA (Hoffman 1997), Columbia (Rogers & Santosh 2002), or Paleopangea (Piper 2010). Reddy & Evans (2009) advocate the name NUNA because it is older than the name Columbia. However, Meert (2012) argues that the NUNA paleocontinent defined by Hoffman (1997) differs little from the NENA proposed by Gower *et al.* (1990). Therefore, if precedence should be considered, this Mesoproterozoic supercontinent should be named NENA. In addition, NENA and NUNA originally refer to correlations between Laurentia, Baltica, Siberia, and eventually East Antarctica, so these reconstructions represent only a fraction of the Paleoproterozoic supercontinent. In this way, Meert (2012) states that the name Columbia proposed by Rogers & Santosh (2002) designates the first attempt of a global and testable reconstruction. After Meert's (2012) reasonings, we will call hereafter the Paleoproterozoic supercontinent as Columbia.

The rupture time of Columbia is a subject of intense discussion in literature. Some authors suggest that Columbia broke-up soon after its formation, as evidenced by the significant amount of mafic dykes dated around 1780-1790 Ma found in North China Craton (Kusky *et al.* 2007), Baltica (Pisarevsky & Bylund 2010), and Amazonian Craton (Reis *et al.* 2013). Nevertheless, such global tectonic and magmatic features are usually associated with Statherian taphrogenesis at different cratons, and so they would not represent a complete rupture of the supercontinent (Brito Neves *et al.* 1995). Indeed, paleomagnetic and geochronological data obtained for Baltica and Laurentia, which formed the Columbia core (e.g. Zhao *et al.* 2002), suggest they remained joined from 1800 Ma until at least 1270 Ma (Salminen & Pesonen 2007). A long-lived Columbia is consistent with the unusual tectonic style that prevailed in the Mesoproterozoic, marked by a strong decrease in the subduction flow and subduction related magmatism (Silver & Behn 2008). This is also coherent with the intense intracratonic magmatic activity that is characterized by the emplacement of a voluminous anorogenic rapakivi granitic magmatism, between 1600 and 1300 Ma, which is one of the most striking features of the continental blocks forming Columbia (e.g. Åhäll & Connelly 1998, Anderson & Morrison 1992, Bettencourt *et al.* 1999, Hoffman 1989, Karlstrom *et al.* 2001, Rämö *et al.* 2003, Vigneresse 2005).

Piper (2010) proposes that the demise of Columbia occurred through a series of small intracratonic rotations that are consistent with U-Pb ages (and Nd model ages), obtained for rocks between 1200 and 1000 Ma. Such period is characterized by a small peak in the formation of juvenile crust, when compared with periods related to the formation of other supercontinents (Hawkesworth *et al.* 2010). Recently, Pisarevsky *et al.* (2014) suggested that the Columbia supercontinent began its agglutination at ~1700 Ma, reaching its maximum area between 1650-1580 Ma. They also argued that Columbia broke-up in two stages. The first one occurred between 1450 and 1380 Ma and the second at ca. 1270 Ma. In contrast, Zhao *et al.* (2004) and Rogers & Santosh (2009) postulated that Columbia's break-up occurred almost synchronously at ca. 1500 Ma.

Almost all continental masses involved in Columbia, later assembled to form the Rodinia supercontinent at about

1100 – 1000 Ma ago (McMenamin & McMenamin 1990). Several paleogeographic reconstructions have been proposed for the Neoproterozoic supercontinent (e.g. Hoffman 1991, Weil *et al.* 1998, D'Agrella-Filho *et al.* 1998, Dalziel *et al.* 2000, Tohver *et al.* 2002, 2006, Pisarevsky *et al.* 2003, Meert & Torsvik 2003, Li *et al.* 2008). Li *et al.* (2008) rebuilt Rodinia including all cratonic areas of the world. However, geological evidence show that some continental blocks that formed the West Gondwana (e.g. Congo-São Francisco, Kalahari) did not take part in Rodinia, since a large ocean existed between these units and the Amazonian Craton (Cordani *et al.* 2003, Kröner & Cordani 2003, D'Agrella-Filho *et al.* 2004, and references therein). After Rodinia break-up, their continental fragments gathered in other configurations (e.g. Gondwana), but the details of this process, including the timing and reassembly configuration of the different blocks, are still a subject of debate in literature, mainly due to the almost total absence of key paleomagnetic poles between 900 and 600 Ma for the units that potentially composed these landmasses.

The Amazonian Craton, in the Northwest of South America, surely played a fundamental role in the Earth's geodynamic history and in the paleogeography of Columbia, Rodinia, and Gondwana. In recent years, a wealth of new paleomagnetic data was obtained for this unit with important implications on the formation and rupture of Columbia and Rodinia supercontinents, and on the agglutination of Gondwana. In Table 1, we list all poles between 2100 and 530 Ma available for the Amazonian Craton and corresponding references.

In this paper, we will discuss the recent paleomagnetic and geological evidence for the participation of the Amazonian Craton in different Proterozoic supercontinents. Firstly, we will introduce the reasoning behind paleogeographic reconstructions based on paleomagnetic data. Then, we will present a brief description of the geologic/tectonic compartments of the Amazonian Craton. The following topics discuss the recent paleomagnetic data and their implications for the participation of the Amazonian Craton in pre-Columbia times, in Columbia supercontinent, in Rodinia supercontinent, and in the Gondwana continent. Finally, the most important conclusions regarding the geodynamic evolution of the Amazonian Craton during the Proterozoic will be shown.

## PALEOMAGNETIC RECONSTRUCTION OF PALEOCONTINENTS

The Pangea was the first supercontinent to be reconstructed on the basis of the fitting of geological provinces, continent shorelines, paleoclimatic indicators, and the continuity of the paleontological record throughout the ancient continental assembly (Wegener 1912). With the advent of isotope geochemistry, radiometric chronology and geophysics, other approaches were incorporated into the exercises of paleocontinent reconstructions, particularly the pre-Pangea supercontinents (Evans 2013), including the age and continuity of large igneous provinces and paleomagnetic data. From these, the only technique that provides a quantitatve assessment of the past distribution of the continents is paleomagnetism (e.g. Butler 1992).

Paleomagnetic poles are equated to the Earth's spinning poles and therefore provide a geographical reference frame for reconstructions. The paleomagnetic method is based on two premises:

1. the Earth's magnetic field when averaged over $10^4$ to $10^5$ years is equivalent to that of a dipole centered in the planet, and aligned along its rotation axis;
2. magnetic minerals record and preserve the orientation of the ancient field over geological time scales.

The first premise is also known as the geocentric axial dipole (GAD) hypothesis, and seems to hold for recent and ancient times (Meert 2009, Swanson-Hysell *et al.* 2009). The field sampling must then comprise sites distributed within at least tens to hundreds of thousand years. This is the reason why several dykes or sedimentary strata must be sampled to determine a single paleomagnetic pole.

For ensuring that a paleomagnetic pole calculated for a given geological formation fits the GAD assumption, we must comply with minimum statistical standards (e.g. number of samples larger than 24; confidence circle around the pole smaller than 16°; van der Voo 1990). In addition, paleomagnetic directions for a given target must preferentially include normal and reversed directions, thus proving that enough time has elapsed during the eruption, intrusion or deposition of the studied geological unit. The second premise of paleomagnetism assumes that the orientation of the geomagnetic field, when the rock unit was formed, is preserved until today in its magnetic remanence vector. However, we know that different geological processes, such as metamorphism or diagenesis, can change the original magnetization by re-heating original magnetic grains or creating new ones (van der Voo & Torsvik 2012). Usually, this change overprints the original magnetization only partially and a single sample may therefore record two or more remanence vectors.

Classically, we apply the stepwise demagnetization techniques to deconvolve the different components of the natural remanence vector; the remanence unblocked in more stable magnetic grains is usually interpreted as the primary one (As & Zijderveld 1958). In order to attest to the primary

**Table 1**. Paleomagnetic poles from the Amazonian Craton between 2100 and 530 Ma.

| Rock unit | Plat (°N) | Plong (°E) | $d_p/d_m$ ($A_{95}$) (°) | Age ± error (Ma) | Q | Ref. |
|---|---|---|---|---|---|---|
| The proto-Amazonian Craton before Columbia | | | | | | |
| a) Tumuc Humac Mount. Granite | 18.9 | 273.7 | 19.2/22.3 | 2100 ± 1 U-Pb zrn | 3 | 1, 2 |
| b) Tampok River Granite | -6.9 | 300.1 | 15.9/16.1 | 2155 ± 3 U-Pb zrn | 3 | 1, 3 |
| c) Mataroni River Granite | 14.9 | 289.2 | 40.6/42.7 | 2115 ± 3 U-Pb zrn | 3 | 1, 2 |
| d) Approuague River Granite | 4.5 | 298.9 | 19.1/19.2 | 2093 ± 3 U-Pb zrn | 3 | 1, 2 |
| e) Approuague River Granite | -5.9 | 296.9 | 34.3/35.1 | 2100–2050 | 3 | 1 |
| f) Approuague River Granodiorite | -18.5 | 294.3 | 21.3/23.0 | 2089 ± 4 U-Pb zrn | 3 | 1, 3 |
| g) Approuague River Granite | 5.3 | 293.4 | 16.8/17.2 | 2050–2070 | 3 | 1 |
| Mean (a–g) - GF1 pole | 1.8 | 292.5 | (11.2) | 2050-2070 | 3 | 4 |
| h) Oyapok granitoids – OYA pole | -28.0 | 346.0 | (13.8) | 2036 ± 14 Ar-Ar amp | 5 | 1, 5 |
| i) Armontabo River Granite – ARMO pole | -2.7 | 346,3 | (14.2) | 2080 ± 4 U-Pb zrn | 4 | 1, 6 |
| j) Imataca Complex – IM1 pole | -49.0 | 18.0 | (18.0) | 1960–2050 | 3 | 7 |
| k) Imataca Complex – IM2 pole | -29.0 | 21.0 | (18.0) | 1960–2050 | 3 | 7 |
| l) Encrucijada Pluton – EN1 pole | -55.0 | 8.0 | (6.0) | 1972 ± 4 Ar-Ar amp | 3 | 8 |
| m) Encrucijada Pluton – EN2 pole | -37.0 | 36.0 | (18) | 1972 ± 4 Ar-Ar amp | 3 | 8 |
| Mean (h-m) - CA1 pole | 43.2 | 21.9 | (16,5) | ~1970 | 3 | 9 |
| n) Costal Late Granite – PESA pole | -56.7 | 25.1 | 6.2/12.4 | 2060 ± 4 U-Pb zrn | 3 | 1, 3 |
| o) Costal Late Granite – ROCO pole | -58.0 | 26.4 | 7.9/15.8 | 2095 ± 6 U-Pb zrn | 3 | 1, 3 |
| p) Costal Late Granite – MATI pole | -58.6 | 25,5 | 9.7/19.4 | ~2050-1970 | 3 | 1 |
| q) Costal Late Granite – ORGA pole | -59.7 | 44.7 | 10.1/19.5 | 2069 ± 4 U-Pb zrn | 3 | 1, 3 |
| Mean (n-q) - GF2 pole | -58.5 | 30.2 | (5.8) | ~2050-1970 | 3 | 4 |
| Roraima Uairen Fm. – U2 pole | -66.5 | 9.0 | (17.8) | 1920-1830 | 2 | 10, 11 |
| Surumu Group volcanics - SG pole | -27.4 | 54.8 | (9.8) | 1966 ± 9 U-Pb zrn | 5 | 9, 12, 13 |
| The Amazonian Craton in the Columbia supercontinent | | | | | | |
| Roraima Uairen Fm. - U1 pole | -69.0 | 17.0 | (7.2) | 1838 ± 14 U-Pb fl | 4 | 10, 11 |
| Aro-Guaniamo dike (group II) | -42.0 | 0.0 | (6.0) | 1820 mean Ar-Ar bi | 4 | 8 |
| Colider Group (rhyolites) – CG pole | -63.3 | 298.8 | (10.2) | 1789 ± 7 U-Pb zrn | 4 | 14 |
| Avanavero Sills – AV pole | -48.4 | 27.9 | (9.6) | 1788.5 ± 2.5 U-Pb badd | 5 | 15, 16 |
| Basic dykes (group I) | 59.0 | 222.0 | (6.0) | 1800-1500 | 4 | 8 |
| Kabaledo dykes | 44.0 | 210.0 | (14.3) | 1800-1500 | 2 | 17 |
| La Escalera basic dykes (group 1) | 55.5 | 225.5 | (11.2) | 1800-1500 | 4 | 8 |
| Parguaza G3N | 10.7 | 294.7 | (25.0) | 1545-1393 | 1 | 18, 19, 20 |
| Parguaza rapakivi batholith G1R | 54.4 | 173.7 | (9.6) | 1545-1392 | 1 | 18, 19, 20 |
| Mean Mucajai/Parguaza complex | 31.7 | 186.6 | (22.8) | ~1530 | 2 | 21 |

Continue...

Tabela 1. Continuation.

| Rock unit | Plat (°N) | Plong (°E) | $d_p/d_m$ ($A_{95}$) (°) | Age ± error (Ma) | Q | Ref. |
|---|---|---|---|---|---|---|
| Guadalupe Gabbro (Component A) | 38.9 | 306.2 | (13.7) | 1531 ± 16 U-Pb zrn | 4 | 22 |
| Roraima dolerites, younger component | 63.0 | 231.0 | (8.8) | 1468 ± 3 Ar-Ar pl | 2 | 8 |
| Rio Branco sedimentary rocks – A1 pole | -45.5 | 270.0 | (6.5) | 1440-1544 U-Pb | 4 | 23, 24 |
| Salto do Céu sills – A2 pole | -56.0 | 278.5 | (7.9) | 1439 ± 4 U-Pb badd; 981 ± 2 Ar-Ar wr | 5 | 23, 25, 26 |
| Nova Guarita dykes – A3 pole | -47.9 | 245.9 | (7.0) | 1418.5 ± 3.5 Ar-Ar bi | 6 | 27 |
| Indiavai dykes – A4 pole | -57.0 | 249.7 | (8.6) | 1415.9 ± 6.9 U-Pb zrn | 4 | 28, 29 |
| Nova Lacerda mafic dykes | -0.5 | 310.7 | (17.9) | 1380 ± 32 Rb-Sr | 2 | 30, 31 |
| The Amazonian Craton: Rodinia's prodigal son | | | | | | |
| Nova Floresta formation – NF pole | 24.6 | 164.6 | (6.2) | 1198 ± 3 Ar-Ar bi | 5 | 32 |
| Fortuna formation – FT pole | 59.8 | 155.9 | (9.5) | 1149 ± 7 U-Pb x | 5 | 33 |
| The Amazonian Craton in Gondwana | | | | | | |
| Puga Cap carbonate – A pole | -82.6 | 292.6 | (7.2) | 627 ± 30 Pb-Pb wr | 4 | 34 |
| Puga Cap carbonate – B pole | 33.6 | 326.9 | (8.4) | 530-520* | 2 | 34 |

Plat: Paleolatitude; Plong: Paleolongitude; $d_p/d_m$ ($A_{95}$) (in degrees): Fisher's statistical parameters. Geochronological symbols – zrn: zircon; badd: baddeleyite; bi: biotite; pl: plagioclase; fl: fluorapatite; x: xenotime; amp: amphibole; wr: whole rock; Q: quality factor (van der Voo 1990); *: inferred from the Gondwana apparent polar wander path. References of the table: 1 – Théveniaut *et al.* (2006); 2 – Vanderhaeghe *et al.* (1998); 3 – Delor *et al.* (2003); 4 – D'Agrella-Filho *et al.* (2011); 5 – Nomade *et al.* (2001); 6 – Enjolvy (2004); 7 – Onstott & Hargraves (1981); 8 – Onstott *et al.* (1984a); 9 – Bispo-Santos *et al.* (2014a); 10 – Castillo & Costanzo-Alvarez (1993); 11 – Beyer *et al.* (2015); 12 – Fraga & Dreher (2010); 13 – Schobbenhaus *et al.* (1994); 14 – Bispo-Santos *et al.* (2008); 15 – Bispo-Santos *et al.* (2014b); 16 – Reis *et al.* (2013); 17 – Veldkamp *et al.* (1971); 18 – Valdespino & Costanzo-Alvarez (1997); 19 – Gaudette *et al.* (1978); 20 – Bonilla-Pérez *et al.* (2013); 21 – Veikkolainen *et al.* (2011); 22 – Bispo-Santos (2012); 23 – D'Agrella-Filho *et al.* (2016); 24 – Geraldes *et al.* (2014); 25 – Teixeira *et al.* (2016); 26 – Elming *et al.* (2009); 27 – Bispo-Santos *et al.* (2012); 28 – D'Agrella-Filho *et al.* (2012); 29 – Teixeira *et al.* (2011); 30 – Tamura *et al.* (2013); 31 – Girardi *et al.* (2012); 32 – Tohver *et al.* (2002); 33 – D'Agrella-Filho *et al.* (2008); 34 – Trindade *et al.* (2003).

nature of a remanence direction, we use paleomagnetic stability tests, such as the baked contact test, the fold test, and the conglomerate test (see details in Butler 1992). In addition, the direction must be different from the paleomagnetic directions obtained in younger geological units of the same region. van der Voo (1990) summarized the checks conceived to attest if the two basic assumptions of paleomagnetism were valid. Furthemore, van der Voo stablished that a reference paleomagnetic pole must have been obtained in a geological unit in structural continuity to the cratonic block and must have a precise dating (error within 4%).

With reference paleomagnetic poles in hand, one can define the ancient position of continents based on their Euler rotations. The Euler theorem implies that any displacement in the surface of a sphere is equivalent to a single rotation about a fixed axis. Thus, to drive any continental mass back to its ancient position, we just need a rotation pole and the rotation angle around it. In this way, the confirguration of a paleocontinent can be expressed as a series of rotation poles and angles and as such they can be tested with new paleomagnetic poles or through the other approaches cited before. Euler pole reconstructions of continent motions date back to the work of Bullard *et al.* (1965), but until recently several reconstructions are still performed by cutting and pasting continents on flat maps, thus distorting their contours and providing models that are sometimes unrealistic and not testable. Nowadays, several softwares enable to easily reconstruct the global geography in three-dimensions using rotation angles and poles (e.g. GPlates, Williams *et al.* 2012, GMap, Torsvik & Smethurst 1999).

The paleomagnetic approach to paleocontinent reconstructions has nevertheless some drawbacks: the most important is the ambiguity in polarity given the axial symmetry of the GAD model (Fig. 1). Because of that, a paleomagnetic pole allows one to assign a paleolatitude and a paleodeclination (rotation from present-day North) for a continent but not the hemisphere or longitude it belonged to in the past. Therefore, to deduce the paleolongitude and polarity of different continental masses in paleogeographic reconstructions, one must use additional information other than paleomagnetism. In the further discussion, we attempted to complement the paleomagnetic information for the

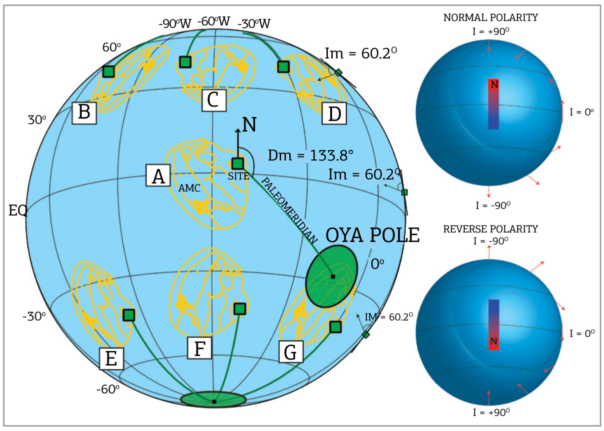


Figure 1. Amazonian craton (AMC) and geologic/geocronological provinces (yellow lines) reconstructed with the OYA pole. Amazonian craton is shown in its present position (A) with South American coastline. Also shown is the local geographic position of the Oyapok granites and their respective pole (with confidence circle) in green. Paleomeridian line passing through the sampling site and paleomagnetic pole is also shown. Positions B to G show that the continent can be moved freely along the same latitude for the two choices of polarity: Normal (B, C and D) or Reverse (E, F and G). $D_m$ and $I_m$ are, respectively, the mean declination and inclination of characteristic remanent magnetization direction calculated for the OYA rocks. "Normal polarity" and "reverse polarity" globes on the right show the configuration of inclination (I, red arrows) for each case.

Amazonia Craton and surrounding cratonic blocks with the most updated geological data available in the literature.

## THE AMAZONIAN CRATON

The Amazonian Craton is one of the largest cratonic areas in the world, with about four million square kilometers (Fig. 2a). It is exposed in two major areas divided by the Phanerozoic Amazon Basin: the Guiana Shield to the North and the Brazil-Central Shield (also known as Guaporé Shield) to the South (Schobbenhaus *et al.* 1984, Santos *et al.* 2000, Lacerda-Filho *et al.* 2004). According to recent syntheses of Tassinari *et al.* (2000), Delor *et al.* (2003), Santos *et al.* (2003), and Cordani & Teixeira (2007), the evolution of the Amazonian Craton is marked by successive accretionary events with greater or lesser involvement of the juvenile crust occurred from the Paleoproterozoic to the Neoproterozoic.

Based on geochronological data, Tassinari & Macambira (1999, 2004) proposed an evolutionary model for the Amazonian Craton, which began when Hadean-Archean microcontinents assembled along Paleoproterozoic collisional orogens between 2200 Ma and 1950 Ma. This was followed by the development of a succession of magmatic arcs and collisional processes involving the reactivation and reworking of pre-existing rocks. Two models that subdivide

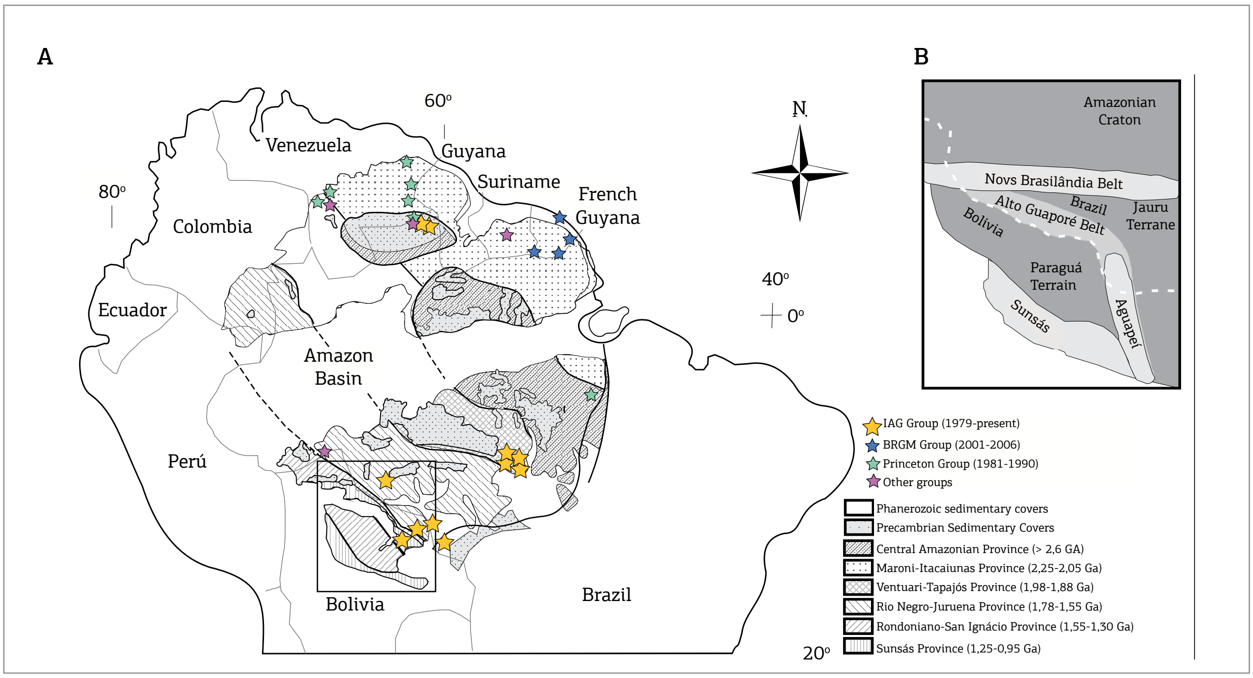


Figure 2. (A) Amazonian Craton and their geologic/geochronological provinces (adapted from Cordani & Teixeira 2007 and Bettencourt *et al.* 2010). The stars indicate approximate geographical locations of geological units studied by the following research groups: Princeton – blue; BRGM – green; IAG-USP – yellow; other groups – purple. (B) Sketch of the southwestern part of the Amazonian Craton showing Paraguá Terrain and Alto Guaporé, Sunsás, Aguapeí, and Nova Brasilândia belts (modified after D'Agrella-Filho *et al.* 2012).

the Amazonian Craton into geochronological provinces have been proposed, one by Tassinari & Macambira (1999, 2004) and the other by Santos *et al.* (2003). We followed the model of Tassinari & Macambira (1999, 2004) (Fig. 2A), which is adopted by several other authors (e.g. Schobbenhaus *et al.* 2004, Cordani & Teixeira 2007, Cordani *et al.* 2010, Bettencourt *et al.* 2010).

The oldest portion (Hadean-Archean) of the Amazonian Craton (Central Amazonian Province) consists of granite-greenstone terrains and high-grade metamorphic rocks exposed in the Brazil-Central and Guiana shields (Tassinari & Macambira 2004, Nadeau *et al.* 2013). The Maroni-Itacaiúnas Belt separates these landmasses, and it is dated around 2250-2050 Ma (Ledru *et al.* 1994). The Hadean-Archean basement is covered by volcano-sedimentary sequences with little or no deformation and ages ranging between 1980 and 1400 Ma. The southwestern part of the Hadean-Archean core was accreted by subduction-related juvenile magmatic arcs, which formed the Ventuari-Tapajós (1980-1810 Ma) and Rio Negro-Juruena (1780 – 1550 Ma) Provinces (Tassinari & Macambira 1999, Tassinari *et al.* 2000, Pinho *et al.* 2003, Schobbenhaus & Brito Neves 2003, Cordani & Teixeira 2007).

During the Mesoproterozoic, subduction-related magmatic arcs were developed between 1600 Ma and 1300 Ma (e.g. Jauru Terrain in Mato Grosso State), forming the Rondoniano-San-Ignacio Province until the final collision of Paraguá Terrain at about 1320 Ma ago (Bettencourt *et al.* 2010). This collisional model has been extended to the northwestern Rondônia State, with the recognition of the Trincheira ophiolite by Rizzotto & Hartmann (2012), who interpreted it as an oceanic crust fragment raised during the Mesoproterozoic as a consequence of the collision between the Paraguá Terrain and the proto-Amazonian Craton along the Alto Guaporé Belt (Fig. 2B). The E-W Nova Brasilândia Belt (NBB – 1100 – 1000 Ma old) at North of the Paraguá Terrain (Fig. 2b) most likely represents intracratonic reactivations that occurred during the development of Sunsás orogen (Sunsás Province – 1250 – 1000 Ma), which is located on the southwestern tip of the Amazonian Craton, in the Bolivian region (Litherland *et al.* 1989, Boger *et al.* 2005, Santos *et al.* 2008, Teixeira *et al.* 2010, Cordani *et al.* 2010). Some authors, however, interpret the NBB as a result of the collision between the proto-Amazonian Craton and the Paraguá Terrain, which would extend to Mato Grosso State, including the Jauru Terrain (Tohver *et al.* 2004a).

The Aguapei Belt (Fig. 2B) is considered a branch to the north of the Sunsas belt, separated from the main part of the orogeny by the Paraguá Terrain. This belt has been interpreted as an aborted continental rift, whose deposition initiated at ca. 1300 Ma, followed by compression and thrusting to the east at ca. 1000 Ma (Litherland *et al.* 1989, Sadowski & Bittencourt 1996).

## THE PROTO-AMAZONIAN CRATON BEFORE COLUMBIA

The definition of a crustal paleogeography for the period prior to Columbia formation is yet very speculative, since many continental blocks were still being assembled during this period, including the Amazonian Craton, Laurentia, and Baltica. Well-dated paleomagnetic poles for the different fragments that later were assembled in these cratons are scarce, thus we can only speculate about the possible presence of Archean supercratons, as are the cases of Zingarn (Zimbabwe/Rhodesia/Yilgarn) and Vaalbara (Kaapvaal/Pilbara) supercratons proposed by Smirnov *et al.* (2013) and de Kock *et al.* (2009), respectively. In Amazonia, some authors advocate a relation between the Guiana Shield and the West Africa Craton forming a single, large cratonic block (supercraton) at about 2000 Ma ago (Onstott & Hargraves 1981, Nomade *et al.* 2003, Johansson 2009, Evans & Mitchell 2011).

Despite the general scarcity of Precambrian paleomagnetic data for the Amazonian Craton, the interval between 2100 and 1970 Ma is relatively well represented in the database as a result of studies carried out by two research groups at different times. These studies led to the construction of apparent polar wander paths (APW Paths) for the Amazonian Craton (Guiana Shield) and the West Africa Craton for Orosirian times. In the 1980s, the Princeton group (led by Tullis C. Onstott) conducted a series of paleomagnetic and geochronological studies on intrusive rocks from Guiana Shield (Venezuela and Guyana; see localizations of the studied geological units in Fig. 2 – green stars) and West Africa Craton (Onstott & Hargraves 1981, Onstott *et al.* 1984a, 1984b). Based on the available paleomagnetic data, these authors argued that Guiana Shield was an extension of West Africa Craton, however, it was displaced in relation to the Pangaea reconstruction in such way that the Guri lineament in Guiana Shield and Sassandra lineament in West Africa Craton were aligned (Onstott & Hargraves 1981).

In the beginning of the last decade, researchers from the *Bureau de Recherches Géologiques et Minières* (BRGM, in France) extended the studies of the Princeton group using granitic and metavolcanic rocks exposed in the French Guiana (see localizations of studied geological units in Fig. 2 – blue stars), and also from West Africa Craton (Nomade *et al.* 2001, 2003). APW Paths were constructed for West Africa Craton and Guiana Shield for the time interval 2100 – 1990 Ma (Nomade *et al.* 2003). Such authors showed that both

APW Paths overlap at about 2020 Ma, if the paleogeographic configuration suggested by Onstott & Hargraves (1981) was used. Subsequently, Théveniaut *et al.* (2006), also from the BRGM, presented a comprehensive paleomagnetic and geochronological study regarding plutonic and metamorphic rocks from Guiana Shield, in which they tried to accurately identify the age of magnetization acquisition of the studied rocks, based on several U-Pb and Ar-Ar datings of minerals with different closure temperatures. According to a new group of poles and the reinterpretation of previous paleomagnetic poles, Théveniaut *et al.* (2006) proposed a new APW Path for the Amazonian Craton (Guiana Shield), between 2155 and 1970 Ma. However, they did not discuss the paleogeography proposed by Onstott & Hargraves (1981), which was corroborated by Nomade *et al.* (2003).

Recently, new paleomagnetic data were obtained for felsic volcanic rocks from the Surumu Group (Guiana Shield), which is well dated at 1960-1980 Ma by the U-Pb method (Bispo-Santos *et al.* 2014a). A robust paleomagnetic pole (Tab. 1) was obtained for these rocks, which helps to better define the APW Path traced by Théveniaut *et al.* (2006) between 2070 and 1970 Ma for the Guiana Shield (Fig. 3). This APW Path began being defined by a series of paleopoles concentrated on northern South America, which Théveniaut *et al.* (2006) associated with the Orosirian deformation event (2070-2050 Ma) that affected the French Guiana. An average paleopole designated GF1 (Fig. 3, Tab. 1) was determined for this set of poles (D'Agrella-Filho *et al.* 2011). Eastward, the curve passes over the ARMO and OYA poles (Tab. 1) determined for granites collected over the Armontabo and Oyapok rivers, respectively, whose first letters provided the acronyms of their poles. The age of these poles was defined by dating different minerals (zircon, amphibole and biotite) representing distinct closure temperatures associated with their isotopic systems.

Théveniaut *et al.* (2006) interpret the 2020 ± 4 Ma Ar-Ar age (amphibole) obtained for an Oyapok River granite as the one that best agrees with the blocking temperature of the magnetic mineral (magnetite), which records the geomagnetic field at the time of formation of these rocks, which yielded the OYA pole. The youngest part of the curve is established by two sets of poles: the first corresponds to the poles determined for the Imataca Complex (IM1, IM2 – Tab. 1) and the La Encruzijada Granite (EN1, EN2 – Tab. 1), which are integrated into a single average paleopole called CA1 (Fig. 3, Tab. 1). The second set comprises four poles determined for granitic rocks of northern French Guiana (Théveviaut *et al.* 2006), whose average is represented by GF2 (Fig. 3, Tab. 1). An approximate age of 1970 Ma was suggested by Théveniaut *et al.* (2006) for this part of the curve, based on the 1972 ± 4 Ma age ($^{40}Ar/^{39}Ar$ in amphibole) obtained for the La Encruzijada granite (Onstott *et al.* 1984b). A similar age (ca. 1970 Ma) was also suggested based on the Imataca Complex thermal history, disclosed by hornblende, biotite, and feldspar Ar-Ar dating (Onstott *et al.* 1989).

Finally, the recent ~1960 Ma pole (SG in Tab. 1) determined for the acid volcanic rocks from the Surumu Group (Bispo-Santos *et al.* 2014a) may indicate an extension of the APW Path traced by Théveniaut *et al.* (2006) for the interval 2070-1970 Ma (Fig. 3). In Fig. 3, the APW Path traced by Nomade *et al.* (2003) for West Africa, referring

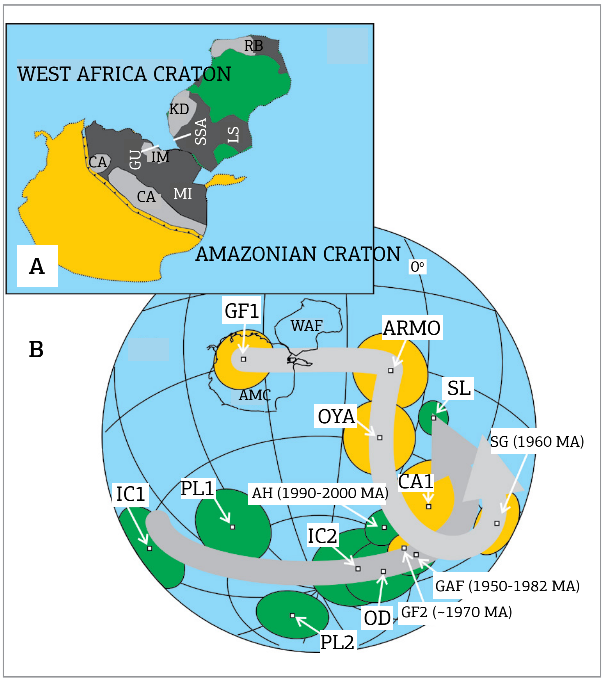


**Figure 3. (A) Paleogeographic configuration of the Amazonian Craton and West Africa Craton link at around 2000-1970 Ma ago. Geotectonic provinces: Amazonia (CA – Central Amazonian Province, MI – Maroni-Itacaiúnas Province; GU – Guri lineament); West Africa (LS – Leo Shield, KD – Kenemanan Domain, RB – Requibat Shield, SSA – Sassandra lineament). (B) Comparison of the Amazonian and West African 2070-1960 Ma APW Paths. Pole Acronyms: AMC – Amazonian Craton (yellow); GF1, ARMO, OYA, GF2 and SG poles (Tab. 1); WAF – West Africa Craton (green); IC1 –Ivory Coast Granites (Nomade *et al.* 2003); PL1 – *Abouasi* Amphibolites (Piper & Lomax 1973); PL2 – *Abouasi* Dolerites (Piper & Lomax 1973); OD – Liberia Granites (Onsttot & Dorbor 1987); IC2 – *Ferke* Granites – *Ivory Coast* (Nomade *et al.* 2003); GAF – *Aftout* Granites (Nomade *et al.* 2003); AH – *Harper* Amphibolite – Liberia (Onsttot *et al.* 1984a); SL – *Aftout* Gabbros – Algeria (Nomade *et al.* 2003). West Africa Craton and their corresponding paleomagnetic poles were rotated using the Euler pole at 43.3°N; 330.5°E (rotation angle of -71.5°). Modified after Bispo-Santos *et al.* (2014a).**

to the time interval 2080 – 1940 Ma, is also shown, after rotation of West Africa and corresponding paleomagnetic poles using an Euler pole located at 43.3°N; 330.5°E (rotation angle of -71.5°). The proto-Amazonian/West-African paleogeography (Fig. 3) is similar to that proposed by Onstott & Hargraves (1981), in which the Guri (Guiana Shield) and Sassandra (West Africa) shear zones were part of the same tectonic lineament. Despite the poor quality of the poles applied to trace the West Africa Craton's APW Path (Nomade *et al.* 2003), the two paths are clearly different for ages older than 2000 Ma, and seem to joint at younger ages (1980 – 1960 Ma), attesting the validity of the formation of this supercraton at about 1980-2000 Ma (Bispo-Santos *et al.* 2014a) (Fig. 3).

According to Bleeker (2003), during Archean to early Proterozoic transition, there would have been a favorable scenario to the presence of many independent 'supercratons'. Between 2500 and 2000 Ma, a diachronic fragmentation would have occurred in the larger supercratons generating around 35 independent cratons, which later on amalgamated into larger continental blocks (e.g. Laurentia) that ultimately formed the Columbia Paleo-Mesoproterozoic supercontinent (Bleeker 2003).

Based on the available paleomagnetic and geologic-geochronological data, we can attempt to reconstruct a proto-Amazonian Craton and its relation with other cratonic blocks at ca. 2000 Ma. In general, the paleomagnetic poles from the Amazonian Craton are compared with those from Laurentia and Baltica aiming supercontinental reconstructions. As already stressed, at times prior to Columbia formation, however, any reconstruction must be considered very speculative, since the major cratonic masses that would be assembled in Columbia were still not completely formed. For example, most of Laurentia was only assembled at ca. 1850 Ma, after the following collisions: Archean Slave and Rae blocks at 1970 Ma; the Slave/Rae and Hearne blocks at 1920 Ma; and this block with the Superior Craton at 1850 Ma (Mitchell *et al.* 2014). Following well-dated paleomagnetic poles from Slave and Superior cratons in the interval between 2200 Ma and 2000 Ma, Mitchell *et al.* (2014) demonstrate that these blocks were separated by a very large ocean (Manikewan Ocean) at ca. 2000 Ma (see Fig. 7 in Mitchell *et al.* 2014). In their reconstruction, the Slave block was rotated -79° around an Euler pole at 52°N, 356°E relative to the Superior block. Using this reconstruction, we propose a possible paleogeography at 2000 Ma (Fig. 4) that tentatively includes other two cratonic blocks of Laurentia (Rae and Hearne), and also parts of Baltica, Amazonia, and West Africa, partly based on paleomagnetic poles as further described. The relative paleogeographic positions of Slave and Superior cratons (Mitchell *et al.* 2014) are constrained using the 1998 Ma pole determined for the Minto dykes (pole at 30°N, 183°E, $A_{95}$ = 13°) from the Superior Craton. The Rae and Hearne blocks were positioned between these cratonic blocks.

At that time, Central Amazonia had already been assembled with the collision of Archean blocks along the 2250-2050 Ma Maroni-Itacaiúnas mobile belt (MIMB, Cordani & Teixeira 2007). Since other Archean blocks collided with Central Amazonia along the MIMB during and after its assembly, it is very likely that the craton at such time was a larger landmass. Based mainly on geological/geochronological evidence, Johansson (2009) proposed the SAMBA model for Columbia, in which West Africa and Sarmatia/Volgo-Uralia may be the components of this larger cratonic block. As previously discussed, West Africa was linked to the Guiana Shield at least since 1970-2000 Ma in a position

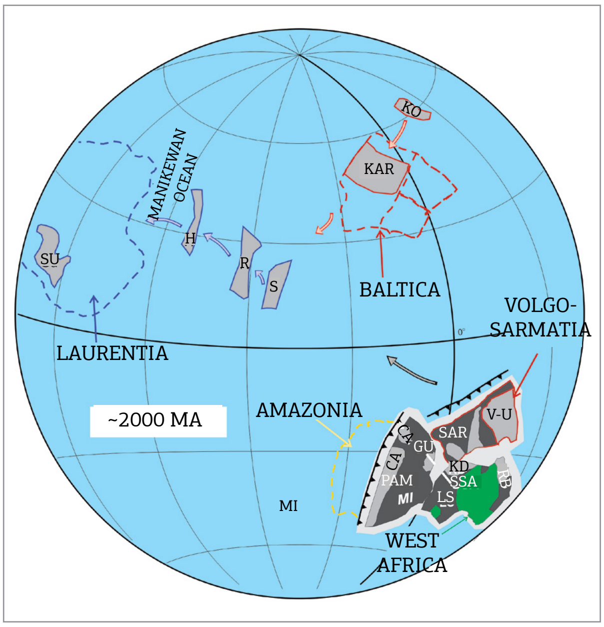


**Figure 4.** Reconstruction at 2000 Ma partially based on paleomagnetic data. Proto-Amazonia (pAM) was constrained using the OYA pole (Tab. 1). Superior Craton (Su) is constrained using the Minto dykes pole (Buchan *et al.* 1998, Evans & Halls 2010). Superior (Su) and Slave (S) relative positions are the same proposed by Mitchell *et al.* (2014) following paleomagnetic data. Karelia (Kar) is constrained by the 1984 Ma Pudozhgora intrusion pole (Lubnina *et al.* 2016), and Kola (Ko) Craton is tentatively positioned close to Karelia. In this scenario, it is suggested that proto-Amazonia, West Africa, Volgo-Uralia (V-U), and Sarmatia (SAR) formed a single cratonic mass. The curved arrows indicate the possible later drifts of each cratonic block. CA – Central Amazonian Province; MI – Maroni-Itacaiúnas Province; GU – Guri lineament; LS – Leo Shield; KD – Kenemanan Domain; RB – Requibat Shield; SSA – Sassandra lineament.

where the Guri (in Guiana Shield) and Sassandra (in West Africa) lineaments were aligned (Onstott & Hargraves 1981, Nomade *et al.* 2003, Bispo-Santos *et al.* 2014a).

At 2000 Ma ago, Baltica was not yet formed either (see Bogdanova *et al.* 2001, 2013). Collision between Sarmatia and Volgo-Uralia (from South and East of Baltica Shield, respectively) occurred between 2100 and 2000 Ma, forming the Volgo-Sarmatia block. Therefore, based on such arguments, we propose herein that a large landmass was already formed at 2000 Ma composed by Volgo-Uralia, Sarmatia, Central Amazonia, and West Africa agglutinated along Paleoproterozoic mobile belts developed up to 2000 Ma. The position of this landmass is constrained by the OYA pole (Tab. 1) obtained for the Oyapok granitoids with an Ar-Ar (amphibole) age of 2020 ± 4 Ma. At that time, active subduction zones were in progress at the Northern and Western margins of Volgo-Sarmatia and Central Amazonia, respectively (Fig. 4).

Karelia and Kola Archaean areas from north-northwestern part of the Baltica Shield were far from Volgo-Uralia and Sarmatia blocks at 2000 Ma (Bogdanova *et al.* 2013). In Fig. 4, the Karelia position was constrained by the 1984 Ma Pudozhgora Intrusion pole (Lubnina *et al.* 2016), and Kola Craton is tentatively positioned close to Karelia. According to Daly *et al.* (2006), after the formation of the Archean Kernoland supercontinent (Pesonen *et al.* 2003), a Wilson cycle was developed between Kola and Karelia after the break-up of this supercontinent at ca. 2500 Ma. This was followed by the formation of an ocean and its later closure, culminating with the docking of Kola and Karelia along the Lapland-Kola orogen at ca. 1900 Ma.

Between 1830 and 1800 Ma, an oblique collision took place between Volgo-Sarmatia with Fennoscandian terrains (Kola-Karelia) along the NW part of Sarmatia (Bogdanova *et al.* 2013). After this oblique collision, Volgo/Sarmatia (together with Central Amazonia and West Africa in our model) performed a counterclockwise rotation that activated older strike-slip faults (Bogdanova *et al.* 2013). These fault systems accommodated mafic dyke swarms with ages between 1790 and 1750 Ma in the Ukrainian Shield (northwestern Sarmatia). At the same time (1790-1780 Ma), profuse mafic intrusions occurred as dykes and sills at the Guiana Shield, spreading over Venezuela, French Guiana and northern Brazil (Reis *et al.* 2013, Bispo-Santos *et al.* 2014b). After Columbia formation at 1780 Ma (Bispo-Santos *et al.* 2014b), minor internal rotations happened associated with 1750 Ma mafic dykes at the Ukrainian Shield (Bogdanova *et al.* 2013).

## THE AMAZONIAN CRATON IN THE COLUMBIA SUPERCONTINENT

According to Rogers & Santosh (2009), the Columbia supercontinent mostly assembled at about 1900-1850 Ma, as suggested by geologic correlations, age constraints, and other lines of evidence, like significant atmospheric changes (Bleeker 2003). However, different paleogeographic scenarios of Columbia were proposed, mainly due to scarcity of high-quality paleomagnetic poles (e.g. Meert 2002, Zhao *et al.* 2002, 2003, 2004, Pesonen *et al.* 2003, 2012, Hou *et al.* 2008a, 2008b, Johansson 2009, Rogers & Santosh 2009, Wingate *et al.* 2009, Yakubchuk 2010, Evans & Mitchell 2011, Zhang *et al.* 2012, Pisarevsky *et al.* 2014; among others).

In recent years, several Paleo-to Mesoproterozoic geological units from the Amazonian Craton were investigated to establish its role in the Columbia Supercontinent. The first paleomagnetic study was conducted on the 1780 Ma felsic volcanic rocks of the Colíder Suite (Bispo-Santos *et al.* 2008), now called Colíder Group, located in northern Mato Grosso State, Brazil-Central (or Guaporé) Shield (Lacerda Filho *et al.* 2004). Based on these results, the paleogeographic scenario visualized for Columbia at 1780 Ma has Laurentia, Baltica, North China and proto-Amazonia aligned in a north to south continental mass forming the core of Columbia Supercontinent (Bispo-Santos *et al.* 2008) (Fig. 5A). Geological evidence favor the hypothesis that proto-Amazonia and North China were laterally disposed at 1780 Ma ago. Subduction-related processes were developed in the western margin of the East Block of North China Craton and along the southwestern proto-Amazonian Craton. This process culminated with the docking of the West Block from North China Craton, along the Trans-North China Belt at ca. 1850 Ma ago, establishing the final configuration of North China Craton. Meanwhile, Ventuari-Tapajós accretion was in progress along the southwestern Amazonian Craton. Cordani *et al.* (2009) restated this interpretation again in a broad discussion on the evolution of the Amazonian Craton and its role in the formation of supercontinents.

Subsequently, paleomagnetic studies on rocks from the Nova Guarita mafic dyke swarm (Bispo-Santos *et al.* 2012) and Indiavaí Intrusive (D'Agrella-Filho *et al.* 2012), also located in Mato Grosso State (Brazil-Central Shield), corroborated the paleogeographic model proposed by Bispo-Santos *et al.* (2008). $^{40}Ar/^{39}Ar$ geochronological dating on biotite and plagioclase minerals separated from four Nova Guarita dykes yielded plateau ages between 1407 ± 8 Ma and 1430 ± 8 Ma. An average of 1418 ± 3 Ma was calculated, which was interpreted as the intrusion age of the dykes (Bispo-Santos *et al.* 2012). A positive baked contact test obtained for one of the dykes that cut the Paleoproterozoic Matupá granite demonstrates the primary nature of the characteristic remanent magnetization (ChRM) isolated for these rocks (see Bispo-Santos *et al.* 2012). The Indiavaí Intrusive belongs to a set of mafic bodies collectively known as Figueira Branca Intrusive Suite (Bettencourt *et al.* 2010). U-Pb dating performed on zircons extracted from Indiavaí and Figueira Branca Intrusives provided ages of 1425 ± 8 Ma and 1415 ± 6 Ma, respectively, which were interpreted as the crystallization times of these bodies (Teixeira *et al.* 2011). Although a baked contact test performed for the Indiavaí Intrusive resulted inconclusive (D'Agrella-Filho *et al.* 2012), similar radiometric

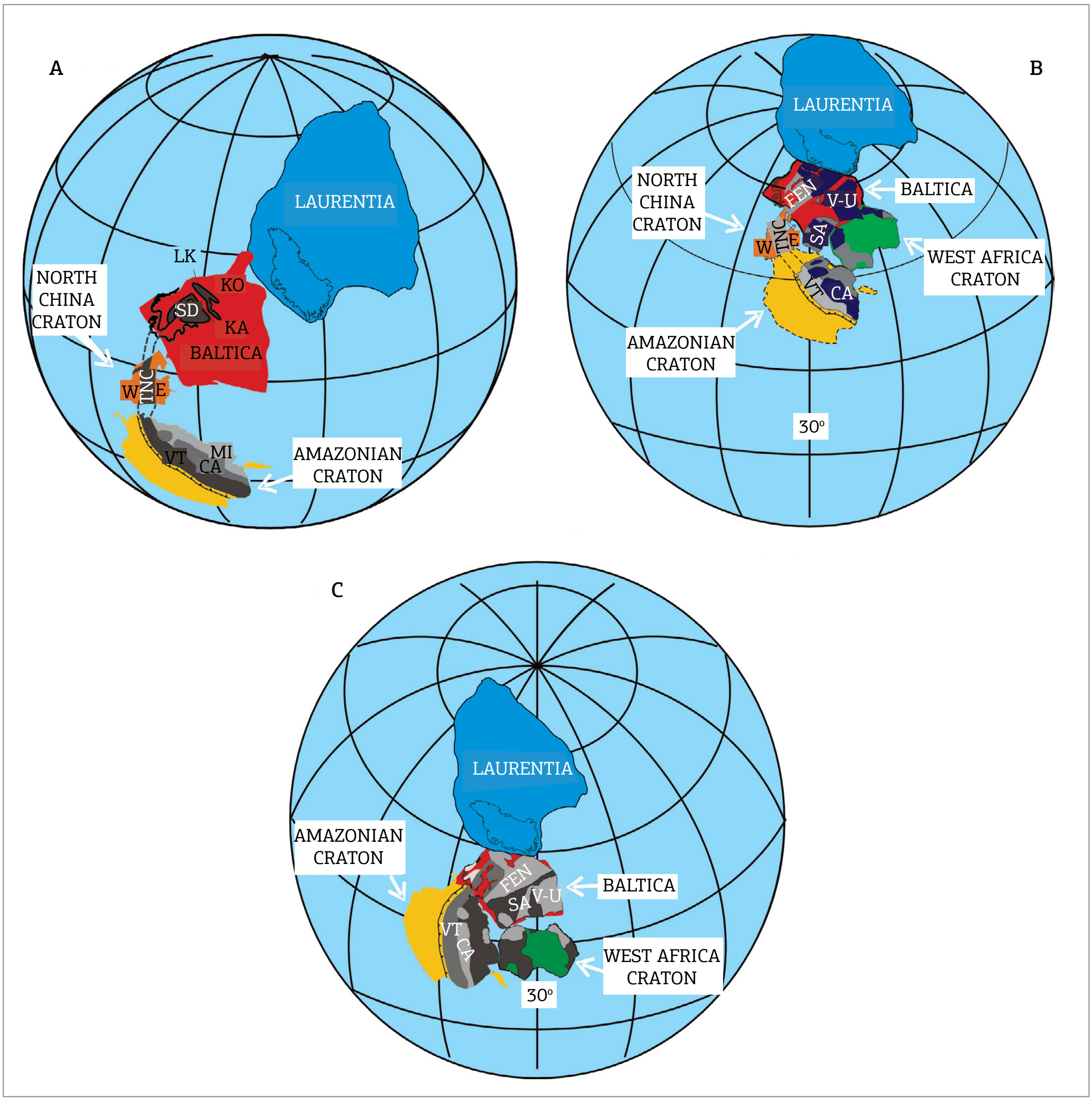


Figure 5. Paleogeographic reconstructions at ~1790 Ma as proposed by: (A) Bispo-Santos *et al.* (2008), (B) D'Agrella-Filho *et al.* (2012), and (C) Bispo-Santos *et al.* (2014b). Baltica (FEN – Fennoscandia; V-U – Volgo-Uralia; SA – Sarmatia; KO – Kola; KA – Karelia; LK – Lapland-Kola; SD – Svecofennian Domain); Amazonia (CA – Central Amazonian Province; MI – Maroni-Itacaiúnas Province; VT – Ventuari-Tapajós Province); and North China Craton (W –West Block; E – East Block; TNC –Trans-North China belt).

ages and ChRM directions obtained for Indiavaí and Nova Guarita rocks strongly suggest they both preserved thermoremanent magnetizations, acquired during rock intrusions at ca. 1415 – 1425 Ma.

These Mesoproterozoic poles (Tab. 1) have important implications regarding the significance of the Nova Brasilândia Belt (NBB – Fig. 2). Based on geophysical data and structural inferences, Tohver *et al.* (2004a) interpreted NBB as a suture zone between the Paraguá Terrain (which, in their view, would also include Mato Grosso area, to the south of NBB) and the proto-Amazonian Craton. This model follows primarily the strong contrast between the monocyclic history of NBB, composed by high pressure and temperature granulites (1090-1060 Ma), and the polycyclic history of the basement rocks to the north, with evidence of sinistral strike-slip deformation dated at 1190 – 1130 Ma (the Ji-Paraná shear zone). Other evidence presented by Tohver *et al.* (2004a) refer to the strong magnetic lineament disclosed by aeromagnetic data, which suggests the continuity of NBB to the east under Serra dos Parecis sedimentary cover. This interpretation, however, contrasts with that of other authors, who suggest that the NBB resulted from intracratonic reactivations during the evolution of Sunsás Belt situated on the southwestern tip of the Amazonian Craton (e.g. Cordani & Teixeira 2007). The similarity of Nova Guarita and Indiavaí poles obtained for geological units situated on opposite sides of NBB supports this latter interpretation (D'Agrella-Filho *et al.* 2012). Nevertheless, the position of these poles, almost perpendicular to NBB, permitted that transcurrent movements along this belt occurred, which might have originated the Ji-Paraná sinistral shear zone previously described.

With regard to the paleogeography of Columbia, the new paleomagnetic data disclosed for Colíder Group (1780 Ma), Nova Guarita dykes (1419 Ma), and Indiavaí Intrusive (1416 Ma) corroborate the model initially proposed by Bispo-Santos *et al.* (2008) (Fig. 5a). In such model, Laurentia, Baltica, North China Craton and proto-Amazonian Craton were laterally disposed, forming the core of Columbia Supercontinent (D'Agrella-Filho *et al.* 2012) (Fig. 5b). West Africa Craton can be included in the model assuming it was linked to the proto-Amazonian Craton (Onstott & Hargraves 1981, Nomade *et al.* 2003, Johansson 2009, Evans & Mitchell 2011, Bispo-Santos *et al.* 2014a). However, some adjustments should be done to accommodate geological information taking into account the uncertainties of the available paleomagnetic poles. Thus, in the Columbia Supercontinent proposed by D'Agrella-Filho *et al.* (2012), Sarmatia was rotated 43° counter-clockwise (Fig. 5b), as suggested by Elming *et al.* (2010), based on paleomagnetic and geological evidence. D'Agrella-Filho *et al.* (2012) also speculated on the presence of a triple junction between Fennoscandia, Sarmatia, North China, and Amazonia (see Fig. 13 in D'Agrella-Filho *et al.* 2012).

According to such model, soon after the formation of Columbia core, around 1850 Ma ago, dextral strike-slip movements occurred between North China and Fennoscandia and sinistral ones between North China and Amazonia/Sarmatia unit. Rupture of North China would be consistent with the profusion of 1780-1790 Ma mafic dykes and sills exposed in northern Brazil, Venezuela and Guyana, known as the Avanavero Large Igneous Province (LIP – Gibbs 1987, Santos *et al.* 2003, Reis *et al.* 2013), with the felsic and mafic dykes from Småland province in southwestern Baltica (Pisarevsky & Bylund 2010); the 1770-1780 Ma gabbros and dolerites belonging to the Ropruchey sills in eastern Fennoscandia (Fedotova *et al.* 1999); and the profusion of similar in age dykes spread over North China (Kusky *et al.* 2007).

Although Paleo to Mesoproterozoic paleomagnetic data of the southeastern Amazonian Craton (Brazil-Central Shield) support a model in which Laurentia, Baltica, North China Craton, and Amazonian/West Africa Cratons were laterally displayed, thus forming the core of Columbia Supercontinent (D'Agrella-Filho *et al.* 2012), in most Columbia models, the Amazonian Craton appears directly linked to Baltica, in a reconstruction called SAMBA connection formally proposed by Johansson (2009).

Recently, a paleomagnetic study was conducted on mafic sills and dykes belonging to the Avanavero LIP, located in northern Roraima State (Guiana Shield). These rocks are very well-dated by the U-Pb method (seven determinations on zircon and baddeleyite), whose 1788 ± 2 Ma mean age is interpreted as the rock crystallization age (Reis *et al.* 2013, Bispo-Santos *et al.* 2014b). A paleomagnetic pole graded with quality factor (Q) five (Tab. 1) was found for the Avanavero event. Studies of magnetic mineralogy, petrography and a positive baked contact test point out to a primary nature of ChRM directions isolated for these rocks (Bispo-Santos *et al.* 2014b).

The Avanavero pole agrees with coeval poles from Baltica and Laurentia, if SAMBA reconstruction is considered, based on geological and geochronological data (Bispo-Santos *et al.* 2014b) (Fig. 5C). Furthermore, we can envisage the agglutination of these masses, starting from the reconstruction at 2000 Ma ago in Fig. 4, in which the landmass formed by proto-Amazonia, West Africa and Volgo-Sarmatia obliquely collided with Fennoscandia, and other cratonic masses that formed Laurentia.

However, the Avanavero pole is very different from the Colider pole, and therefore does not support Columbia's models suggested by Bispo-Santos *et al.* (2008) (Fig. 5A), based on the Colíder pole, and D'Agrella-Filho *et al.* (2012) (Fig. 5B), according to Paleo- to Mesoproterozoic poles. Two hypotheses could be raised to explain this difference:

1. although the rocks have similar ages, their magnetizations were acquired at different times;
2. their magnetizations were obtained during rock crystallization at 1780 to 1790 Ma, however, a relative movement occurred between the two areas after magnetization was acquired by rocks.

If we accept the first hypothesis, four facts lead us to assume that SAMBA model (Johansson 2009) should prevail over those proposed by Bispo-Santos *et al.* (2008) and D'Agrella-Filho *et al.* (2012). Therefore:

1. the Avanavero pole was obtained for anorogenic rocks emplaced in an intracratonic environment (Guiana Shield), whose Hadean-Archean to Paleoproterozoic basement was only partially affected in its southern part by the 1200 Ma K'Mudku event (Cordani *et al.* 2010);
2. the magnetic and petrographic evidence added to a positive baked contact test obtained for Avanavero rocks suggest that their ChRM directions most likely result from thermo-remanent magnetizations acquired during rock cooling at about 1789 Ma ago;
3. no stability tests were performed for the Colíder rocks; Colíder pole was obtained for 1780-1790 Ma felsic rocks from the southern part of Amazonian Craton, where NW-SE magmatic arcs were being formed along the Jauru Terrain up to the final collision of Paraguá Terrain at 1320 Ma (Bettencourt *et al.* 2010). This makes easier to assume that the Colíder pole represents a secondary magnetization;
4. the presently available 1530 Ma paleomagnetic data for Amazonia, Baltica and Laurentia are also consistent with the SAMBA model (Pesonen *et al.* 2012).

On the other hand, if both magnetic records represent the primary magnetization, a possible explanation for the difference in the paleomagnetic poles from Colíder and Avanavero igneous units could be that after their emplacement at 1780 Ma ago, approximately NW dextral strike-slip motions occurred between the northern part of the craton where the Avanavero sills and dykes crop out, and the southern of the craton, in which the acid volcanic rocks from Colíder Group are housed in (Bispo-Santos *et al.* 2014b).

Another interesting fact emerges when the ~1420 Ma Nova Guarita and Indiavaí poles are compared with coeval poles from Baltica and Laurentia, after their rotation to the SAMBA configuration (see Fig. 12 in Bispo-Santos *et al.* 2014b). In such case, a difference between these poles is also observed, which is similar to that of the Avanavero-Colíder poles and once more point to NW dextral movements between the southern part of the Amazonian Craton and the northernmost portions of the Columbia supercontinent. Therefore, it suggests that if these strike-slip movements are real, they must have occurred after 1420 Ma.

In this scenario, the recent recognition of the Trincheira ophiolite in southwestern Amazonian Craton (Rondônia State) suggests that collision of the Paraguá Terrain with the proto-Amazonian Craton along the Alto Guaporé Belt occurred between ~1470 and 1320 Ma (Bettencourt *et al.* 2010, Rizzotto & Hartmann 2012). This collisional event probably originated the NW-SE lineaments (Buiuçu Shear Zone; Almeida *et al.* 2012) observed to the east of Trincheira ophiolite, where mylonitic rocks were dated at 1466.5 ± 1.4 Ma (Ar-Ar on muscovite) and 1467.8 ± 0.8 Ma (Ar-Ar on sericite). These shear zones are interpreted as the result of the Rondonian-San Ignacio orogeny (Cordani *et al.* 1979, Tassinari *et al.* 1996, Almeida *et al.* 2012) that led to the collision of Paraguá Terrain. In face of these facts, Bispo-Santos *et al.* (2014b) speculated that if both paleomagnetic poles represent primary ChRM directions, reactivation of these faults could be, at least partly, responsible for the NW-SE dextral movements implied by the available paleomagnetic data.

Furthermore, later tectonic events affected the Amazonian Craton, which may have produced relative movements between the northern Guiana Shield and the Brazil-Central Shield. We highlight the Late Mesoproterozoic intracratonic displacements associated with the Amazonian Craton/Laurentia collision along the Sunsás-Grenville orogenic belts – e.g. the 1200-950 Ma Aguapeí mobile belt; the ca. 1100 Ma NBB; and NE-SW shear zones associated with ca. 1200 Ma K'Mudku event that affected the southern part of the Avanavero event (Reis *et al.* 2003, Tohver *et al.* 2004a, Teixeira *et al.* 2010, Cordani *et al.* 2010). ENE-WSW to NE-SW shear zones associated with the Rondônia-San-Ignacio rocks in Rondônia State, which were dated at 1300.1 ± 1.4 Ma (plateau Ar-Ar age in muscovite), may have been caused by Sunsás orogen activity (Almeida *et al.* 2012). Also, the polydeformed basement to the north of the NBB is marked by intense shear zones at about 1150 Ma, although mylonitic rocks formed in the tectonic process display a systematic sinistral shear sense in this case (Tohver *et al.* 2004a).

Pisarevsky *et al.* (2014) also discussed the Paleoproterozoic (Colíder and Avanavero) and Mesoproterozoic (Nova Guarita and Indiavaí) poles from Amazonia. They contested the explanation presented by Bispo-Santos *et al.* (2014b) arguing that displacements between the parts of Amazonia are unlikely, as they would disrupt the linearity of the Ventuary-Tapajós province. Alternatively, they propose that Amazonia/West Africa was positioned outboard of the peripheral subduction system comprised by Laurentia and Baltica at 1770 Ma (see Fig. 7 in Pisarevsky *et al.* 2014).

Other models of Columbia, however, are possible, for which smaller mismatches of the Mesoproterozoic poles from Amazonia, Baltica and Laurentia are observed (e.g. Zhang *et al.* 2012, Xu *et al.* 2014, Pehrsson *et al.* 2016). Recently, D'Agrella-Filho *et al.* (2016) presented new paleomagnetic data about the 1440 Ma Salto do Céu mafic sills and sedimentary rocks cut by the sills. Comparison of selected 1460-1400 Ma poles from Baltica and Laurentia with available Mesoproterozoic poles from Amazonia are shown in Fig. 6 for each reconstruction of Columbia proposed by Bispo-Santos *et al.*

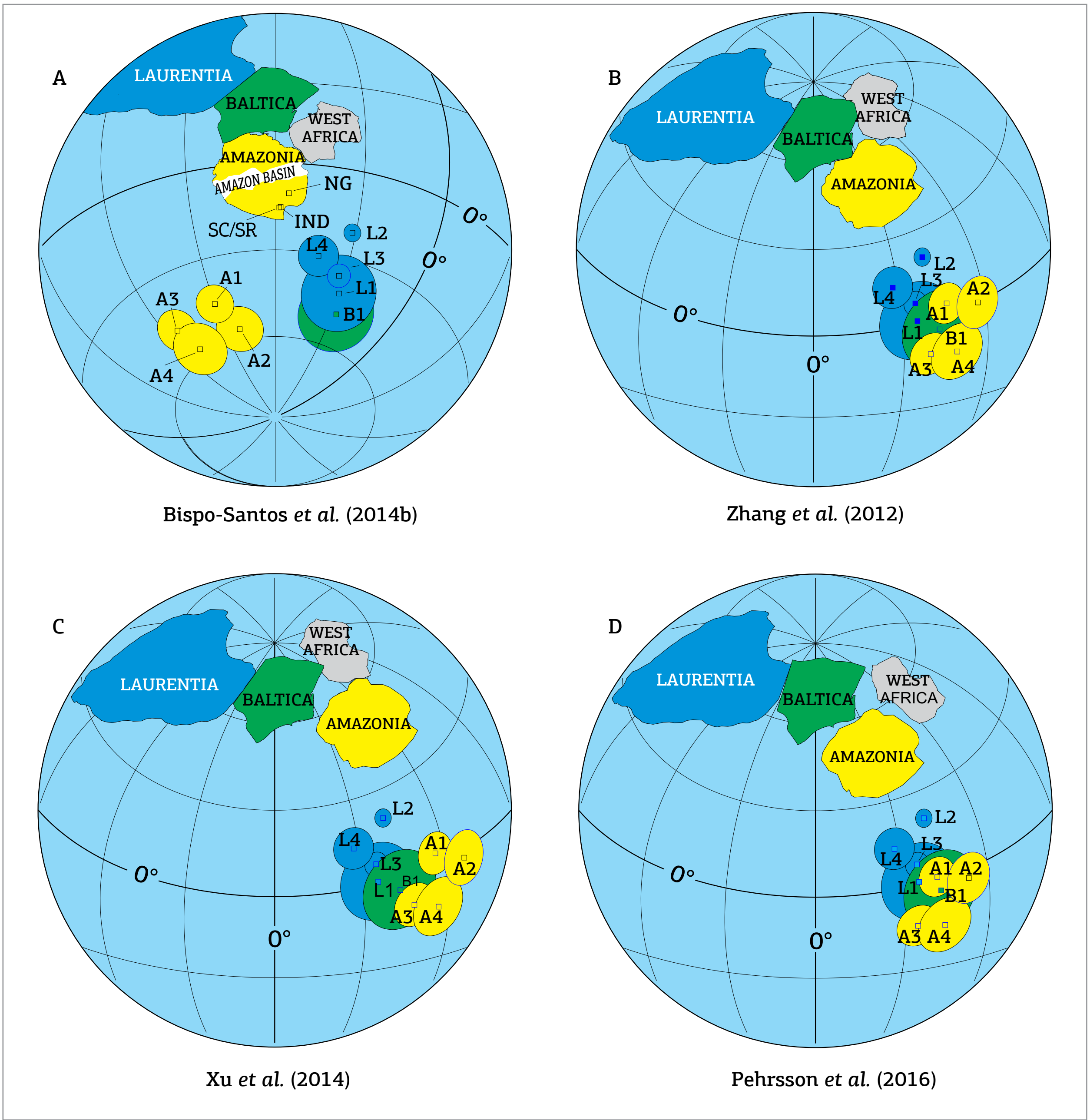


Figure 6. Comparison of Mesoproterozoic poles from the Amazonian Craton, Laurentia, and Baltica considering the reconstruction of Columbia proposed by (A) Bispo-Santos *et al.* (2014b); (B) Zhang *et al.* (2012); (C) Xu *et al.* (2014); and (D) Pehrsson *et al.* (2016) (based on D'Agrella-Filho *et al.* 2016). Mesoproterozoic paleomagnetic poles, and their confidence circles ($\alpha_{95}$): Amazonia – (A1) Rio Branco Sedimentary rocks; (A2) Salto do Céu sills; (A3) Nova Guarita Dykes; (A4) Indiavaí Intrusive (Tab. 1); Baltica – (B1) 1460 Ma mean pole (Bispo-Santos *et al.* 2014b); Laurentia – (L1) 1460 Ma mean pole; (L2) McNamara pole (1401 ± 6 Ma); (L3) Electra Lake Gabbro (1433 ± 2 Ma); (L4) Laramie Anorthosite (1429 ± 9 Ma) (Bispo-Santos *et al.* 2014b). Paleomagnetic poles are represented in the same color of the respective cratonic blocks. Euler rotation poles used for paleomagnetic poles and cratonic blocks as in D'Agrella-Filho *et al.* (2016). Geographical positions of Salto do Céu sills (SC), Rio Branco sedimentary rocks (SR), Indiavaí Intrusive (IND) and Nova Guarita Dykes (NG) are shown in (A).

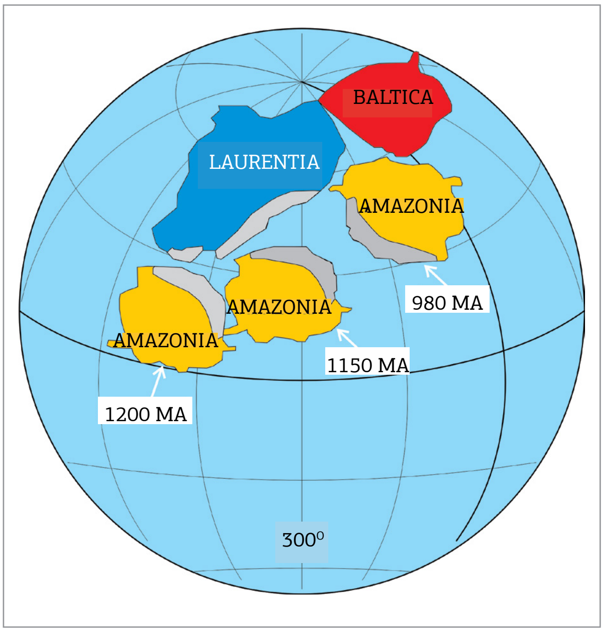


**Figure 7. Geodynamical interaction model of the Amazonian Craton and Laurentia between 1200 Ma and 980 Ma (after Elming *et al.* 2009). Amazonian positions relative to Laurentia (North America in its present position) are shown at 1200 Ma (based on Nova Floresta pole – NF pole in Tab. 1), at 1150 Ma (based on Fortuna Formation pole – FT in Tab. 1), and at 980 Ma (based on Aguapeí sills pole of Elming *et al.* 2009).**

(2014b), Zhang *et al.* (2012), Xu *et al.* (2014), and Pehrsson *et al.* (2016), as seen in Figs. 6a to 6d, respectively. The best cluster of poles is obtained through the reconstruction of Pehrsson *et al.* (2016), in which Amazonia appears rotated counterclockwise relative to the reconstruction of Bispo-Santos *et al.* (2014b) (Fig. 6a), and may indicate internal plate rotations inside Columbia. Note this reconstruction is similar to that proposed by Bispo-Santos *et al.* (2012). Nevertheless, it is clear that new Mesoproterozoic poles from the Amazonian Craton, mainly from the northern Guiana Shield, are required before we decide the best model proposed for Columbia.

## THE AMAZONIAN CRATON: RODÍNIA'S PRODIGAL SON

The Amazonian Craton is one of the largest and most complete fragments of Rodínia's rupture, and possibly the only one of its descendants to take part in the Western Gondwana. Trying to increase our understanding about the paleogeographic evolution and dynamic interaction between Laurentia and the Amazonian Craton, other paleomagnetic investigations were carried out. Sedimentary rocks belonging to the Aguapeí Group and mafic sills cutting these rocks became the targets of paleomagnetic studies performed in western Mato Grosso State by D'Agrella-Filho *et al.* (2008) and Elming *et al.* (2009), respectively. For the study of the Aguapeí Group, redbeds described as belonging to Fortuna Formation (the basal unit) and gray pelitic sedimentary rocks of Vale da Promissão Formation (intermediate unit) were collected close to Vila Bela (next to the Brazil-Bolivia boundary) and Rio Branco (on the other side of the basin) cities, respectively. U-Pb detrital zircon ages ranging from 1453 ± 10 Ma to 1165 ± 27 Ma (n = 89) established the maximum deposition age for the Fortuna Formation at 1165 Ma (Santos *et al.* 2001, Leite & Saes 2003).

The paleomagnetic study of Fortuna Formation rocks enabled isolating ChRM directions carried by diagenetic hematite (D'Agrella-Filho *et al.* 2008). An age of 1149 ± 7 Ma was assigned to Fortuna Formation pole (Tab. 1), based on U-Pb (SHRIMP) dating of authigenic xenotime rims on detrital zircon grains. This paleomagnetic pole, when compared with coeval poles belonging to Laurentia (D'Agrella-Filho *et al.* 2008), seems to support the model proposed by Tohver *et al.* (2004b), which suggests an oblique collision followed by a strike-slip movement between the Amazonian Craton and Laurentia (Fig. 7). A similar model was used to explain the Colombian-Oaxaquian peri-Amazonian fringing arc system (Putumayo orogeny) outboard of Amazonia that evolved during the Amazonia transcurrent movement up to its final collision with Baltica in late Mesoproterozoic times (Ibanez-Mejia *et al.* 2011).

On the other hand, the gray pelitic sedimentary rocks collected near Rio Branco region disclosed reversed ChRM directions, in general, carried by magnetite. The absence of direct geochronological dating of these rocks did not permit to establish the age of the corresponding paleomagnetic pole (D'Agrella-Filho *et al.* 2008).

Paleomagnetic and geochronological studies were also performed on Aguapeí mafic sills (Rio Branco region, Mato Grosso State) cutting the pelitic sedimentary rocks (Elming *et al.* 2009). These sills and dykes belong to Salto do Céu Intrusive Suíte (Araújo-Ruiz *et al.* 2007), but Elming *et al.* called them Aguapeí (hereafter we will use the Salto do Céu original name, see also D'Agrella-Filho *et al.* 2016). In summary, the laboratorial treatments (alternating field – AF and thermal demagnetization) revealed southwest (northeast) directions with downward (upward) inclinations for ten sites (Dm = 11.3°; Im = -57.9°; $\alpha_{95}$ = 8.1°, K = 37), which yielded a paleomagnetic pole (Salto do Céu pole) located at 64.3°S; 271.0°E ($A_{95}$ = 9.2°). An age of 981 ± 2 Ma was determined for one of the sills by $^{40}$Ar-$^{39}$Ar (whole rock). Assigning this age to Salto do Céu pole, Elming *et al.* (2009) proposed a paleogeographic reconstruction, showing the

Amazonian Craton position relative to Laurentia at ~980 Ma ago (Elming *et al.* 2009), which follows the transcurrent model firstly proposed by Tohver *et al.* (2004a, 2004b) and later supported by D'Agrella-Filho *et al.* (2008), as in Fig. 7.

Two facts should be highlighted in this reconstruction:

1. Laurentia paleomagnetic poles in the age range between 1000 and 900 Ma come from high-grade metamorphic rocks related to the Grenville event. The ages of these poles were obtained, in general, from $^{40}Ar$-$^{39}Ar$ single-mineral dating (amphibole, biotite, and plagioclase), and it is not always easy to correlate radiometric and rock magnetization ages;
2. The paleogeographic reconstruction proposed by Elming *et al.* (2009) was based on the transcurrent model of Tohver *et al.* (2004a, 2004b), which shows that the Amazonian Craton at 980 Ma (based on Salto do Céu pole) rotated approximately 180° to its position at 1200 Ma (based on Nova Floresta pole of Tohver *et al.* 2002), during the ~3000 km sinistral motion along the Grenvillian margin (see Fig. 7). Although such large rotations may occur, the final position of the Amazonian Craton to Laurentia is very different from that normally admitted in Rodínia reconstructions (see Weil *et al.* 1998, D'Agrella-Filho *et al.* 1998, Li *et al.* 2008, Ibanez-Mejia *et al.* 2011).

A new U-Pb dating on baddeleyite extracted from Salto do Céu sill (Rio Branco region) has recently yielded an upper intercept age of 1439 ± 4 Ma on the U-Pb concordia diagram, which is interpreted as the crystallization age of the rock (Teixeira *et al.* 2016). This age contrasts with the previous 981 ± 2 Ma Ar-Ar age and enables an alternative interpretation for Salto do Céu sills pole. The new baddeleyite age correlates well with the U-Pb zircon ones of 1471 ± 8 Ma and 1427 ± 10 Ma, respectively, for a gabbro and a granophyre belonging to Rio Branco mafic-felsic Suite (Geraldes *et al.* 2001), suggesting that Salto do Céu sills belong to the same event.

Geraldes *et al.* (2014) presented a provenance study on 100 detrital zircons extracted from Rio Branco sedimentary rocks at Salto do Céu region (their AG-1 sample). The U-Pb determinations showed four age populations for these zircons: 1544, 1655, 1812, and 2515 Ma. The younger population (age peak of 1544 Ma) may represent detrital zircons derived from the Cachoeirinha event rocks (from 1580 to 1520 Ma), and indicate the maximum depositional age for that unit (Geraldes *et al.* 2014). The identification by Ruiz (2005) of xenoliths from these sedimentary rocks inside the Rio Branco igneous rocks (age of 1427 ± 10 Ma) also suggests they are older than those near Vila Bela, whose detrital zircon ages indicate a maximum of 1126 Ma for them (Santos *et al.* 2001, Leite & Saes 2003). These results demonstrate that the pelitic sedimentary rocks previously interpreted as the intermediate unit of Aguapeí Group must in fact be correlated with other sedimentary rocks, probably the Dardanelos Group to the north of the Phanerozoic Serra dos Parecis sedimentary cover (Lacerda-Filho *et al.* 2004). In such case, Salto do Céu sills pole (now dated at 1439 Ma) cannot be used to represent the Amazonian Craton position in the context of Rodínia, and the paleogeographic interpretation made by Elming *et al.* (2009) using this pole should be revised.

Trying to prove the primary nature of the magnetization carried by the sills, recently, D'Agrella-Filho *et al.* (2016) sampled eight new paleomagnetic sites from Salto do Céu sills and samples from five profiles of sedimentary rocks close to the contact with the sills for baked contact tests. The results obtained for the sills and sedimentary rocks are similar to those from Elming *et al.* (2009) and D'Agrella-Filho *et al.* (2008), respectively, in the previous studies of these rocks. More statistically robust paleomagnetic poles were calculated for the sedimentary rocks (A1 pole in Tab. 1 – now called Rio Branco sedimentary rocks pole) and for the sills (A2 pole in Tab. 1) that supersede older poles. Although the baked contact test was inconclusive, because no different magnetization direction was disclosed for sedimentary rocks far from the sills, ages around 1440 Ma for these paleomagnetic poles are supported by the Nova Guarita (1419 Ma) and Indiavaí (1416 Ma) poles. Fig. 6A shows the poles for the sedimentary rocks from Rio Branco area (pole A1), Salto do Céu sills (pole A2), the 1419 Ma Nova Guarita dyke swarm (pole A3), and the 1416 Ma Indiavaí Intrusive (pole A4). All these poles plot close together suggesting similar ages for all of them.

Recently, Evans (2013) (followed by Johansson 2014) proposed an alternate scenario for the dynamic interaction between Laurentia, Baltica, and the Amazonian Craton (see Fig. 3 in Evans, 2013) that totally contrasts with that proposed by Tohver *et al.* (2004b), D'Agrella-Filho *et al.* (2008) and Elming *et al.* (2009). Due to the polarity ambiguity, Evans (2013) argues that a different model may be proposed if we use the Amazonian Craton's anti-poles. In the Evans' model, after SAMBA rupture in Columbia, Baltica and Amazonian Craton performed clockwise rotations, and docked again with Laurentia, the Amazonian Craton faced to Grenville Belt in the present Labrador region. Partially based on paleomagnetic data, Fig. 8 shows a possible dynamic scenario for Columbia rupture, clockwise rotation of Amazonia and Baltica, and posterior collision of these blocks with Laurentia. Paleomagnetic data suggest that Laurentia and Baltica behaved as a unique block at least up to 1265 Ma (Salminen & Pesonen 2007). Fig. 8B provides the configuration of SAMBA connection (after Bispo-Santos

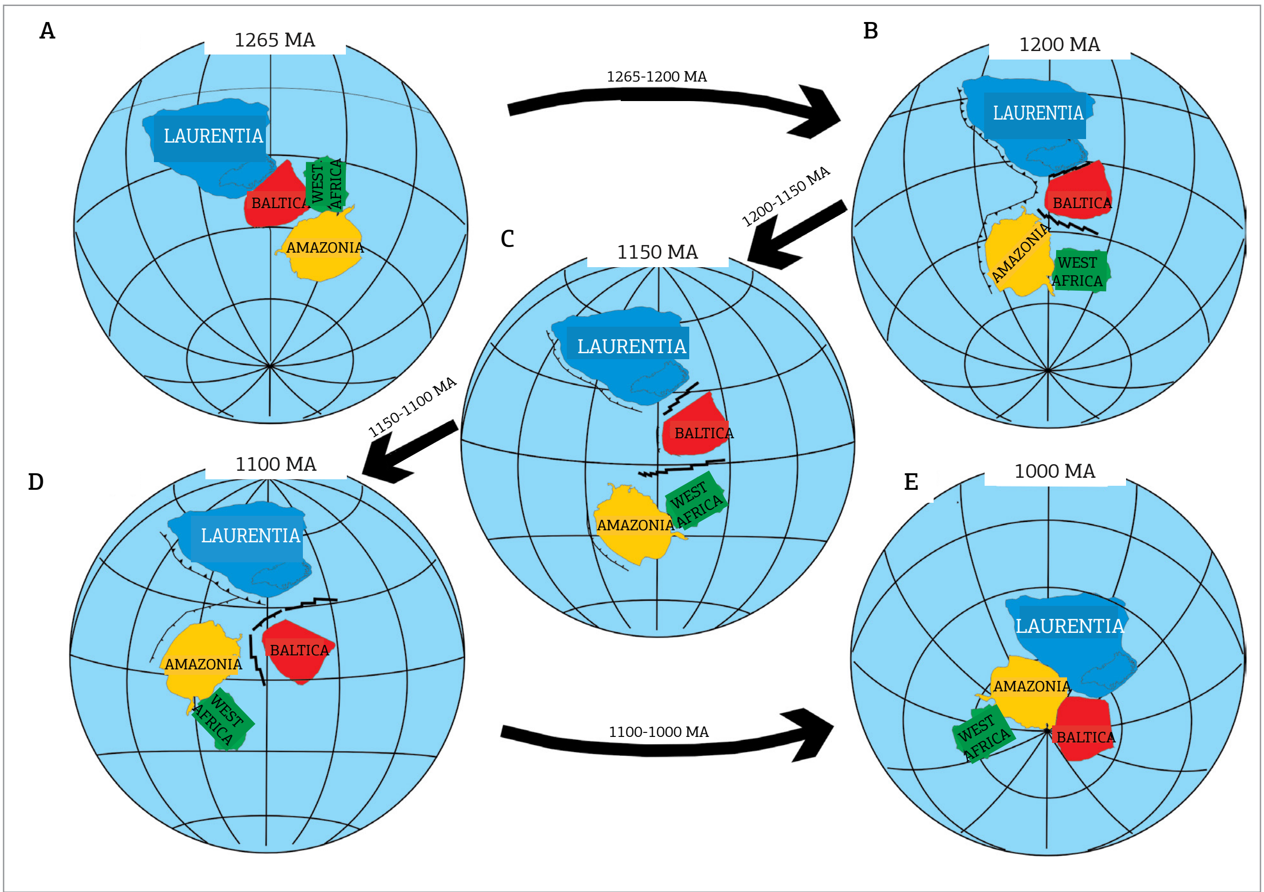


**Figure 8.** Schematic sketch showing rupture of Columbia core (comprised by Laurentia, Baltica, Amazonia, and West Africa), followed by clockwise rotation of Amazonia/West Africa and Baltica and posterior collision with Laurentia forming Rodínia. (A) Reconstruction at 1265 Ma – Columbia core after Bispo-Santos *et al.* (2014b) and Pehrsson *et al.* (2016), positioned by the MacKenzie dykes pole (Buchan & Halls 1990). (B) Reconstruction at 1200 Ma – Laurentia and Amazonia/West Africa were constrained by the Upper Bylot (Fahrig *et al.* 1981, Kah *et al.* 2001) and Nova Floresta poles (Tab. 1), respectively. (C) Reconstruction at 1150 Ma – Laurentia and Amazonia/West Africa were constrained by the Abitibi dykes (Ernst & Buchan 1993, Krogh *et al.* 1987, Irving & Naldrett 1977) and Fortuna Formation poles (Tab. 1), respectively. (D) Reconstruction at 1100 Ma – Laurentia was constrained by the Logan dykes pole (Halls & Pesonen 1982, Davis & Sutcliffe 1985). (E) Reconstruction at 1000 Ma – Laurentia, Baltica, and Amazonia as shown in the reconstruction of Rodínia proposed by Li *et al.* (2008). Euler poles used: Laurentia (14.27°N; 37.04°E; 107.02°); Baltica (21.17°N; 204.26°E; -176.32°); Amazonia (24.21°N; 175.25°E; -150.19°). West Africa was rotated to Amazonia as in Bispo-Santos *et al.* (2014a).

*et al.* 2014b and Pehrsson *et al.* 2016) constrained by the 1267 Ma MacKenzie dykes pole (Buchan & Halls 1990). The Baltica-Laurentia link is practically the same as that proposed by Salminen & Pesonen (2007). It is possible that the MacKenzie dyke swarm is the record of the initial rupture of Columbia (Hou *et al.* 2008b). Fig. 8B presents the configuration at 1200 Ma. Amazonia/West Africa Craton and Laurentia are constrained by Nova Floresta (Tab. 1) and Upper Bylot poles (Fahrig *et al.* 1981), respectively. Baltica and Amazonia/West Africa broke-up and initiated their clockwise rotation. Fig. 8C shows the configuration at 1150 Ma, in which Laurentia and Amazonia/West Africa are constrained by Abitibi dyke (Ernst & Buchan 1993, Irving & Naldrett 1977) and Nova Fortuna poles (Tab. 1), respectively. For the reconstruction at 1100 Ma (Fig. 8D), only Laurentia is constrained by Logan sills pole (Halls & Pesonen 1982, Davis & Sutcliffe 1985). Finally, Fig. 8E introduces the configuration at 1000 Ma as proposed by Li *et al.* (2008), in which Rodínia had already been formed.

## THE AMAZONIAN CRATON IN GONDWANA

Dynamic processes associated with the Amazonian Craton, Laurentia, and Proto-Gondwana between 900 Ma and 530 Ma have been intensively investigated and debated. The period when the Amazonian Craton separated from

Rodínia Supercontinent, as well as the time of its collision with proto-Gondwana, — composed in its western part by the Paranapanema block, the Central Goiás microplate, the Parnaíba block and other smaller blocks underlying the Paraná and Parnaíba Basins — are still in dispute (see Cordani *et al.* 2013a, 2014, Tohver & Trindade 2014).

Many authors advocate a final collision between Amazonian-West African Craton and proto-Gondwana at around 650-600 Ma, after closure of the great Goiás-Pharusian ocean separating these cratonic units in earlier times (e.g. Trompette 1994, 1997, Cordani *et al.* 2000, Cordani & Teixeira 2007, Cordani *et al.* 2013a, 2013b, Ganade de Araújo *et al.* 2014). In this case, late Neoproterozoic would be characterized by the presence of supercontinent Pannotia (Dalziel 1997), comprising all Gondwana units plus Laurentia, the break-up of Laurentia occurring during the Ediacaran with the formation of the Yapetus Ocean (570 Ma, Cawood *et al.* 2001). However, Pannotia formation was contested by Meert & Van der Voo (1997) who declared that Gondwana agglutination occurred in three distinct periods: 800-650 Ma (formation of the Mozambique Belt due to the collision of India, Madagascar, and Sri Lanka with East Africa); 600-530 Ma (formation of the Brasiliano/Pan-African belts through the collision of the South American and African cratonic blocks); and ~550 Ma (formation of the Kuunga belt, which was the result of the collision of Australia and Antarctica with the rest of Gondwana). Thus, east Gondwana would not be completely agglutinated at the time Pannotia is supposed to have existed.

In recent years, several authors have claimed that the final agglutination of the South American core of Gondwana — formed by the Amazonia/Rio Apa, Congo-São Francisco, Rio de la Plata and several other smaller blocks — could have happened during the Cambrian between 550-520 Ma, with the closure of the Clymene Ocean that separated the Amazonian Craton from other continental blocks (Trindade *et al.* 2006).

The paleomagnetic study on carbonate rocks from Araras Group, conducted by Trindade *et al.* (2003), provided a paleomagnetic pole (Puga Cap carbonate A pole in Tab. 1) for the Amazonian Craton, which has been dated at 627 ± 30 Ma (Pb-Pb whole rock isochron obtained for rocks at the base of Araras Group – Babinski *et al.* 2006). When compared with the paleomagnetic poles of proto-Gondwana (including Congo São Francisco and part of East Gondwana), this suggests that the Amazonian Craton was separated from the rest of Gondwana at Ediacaran times. Otherwise, the close fit of the 525 Ma poles from Amazonia and proto-Gondwana (in a Gondwana pre-drift configuration) might show that complete closure of Clymene Ocean occurred only at Ediacaran times (Trindade *et al.* 2006). In the model proposed by Trindade *et al.* (2006), West Gondwana was formed diachronically, similarly to the East Gondwana whose final amalgamation occurred only at 525 Ma (Meert & Van der Voo 1997).

New evidence supporting this interpretation came from paleomagnetic and geochronological studies from remagnetized carbonate rocks collected along the Paraguay Belt (Tohver *et al.* 2010). Collision along the southeastern margin of the Amazonian Craton along the Paraguay Belt produced folding, trusting, and remagnetization dated at 528 ± 36 Ma. According to Tohver *et al.* (2010), the oroclinal inflection of the Paraguay Belt occurred after 528 Ma, which caused the coherent change observed in the ChRM declinations disclosed for rocks collected in the northern and southern inflection areas. Tohver *et al.* (2012) carried out a review regarding the geological, geochronological and tectonic history related to Araguaia, Paraguay and Pampeano belts. These authors show common features for these belts that reflect a shared geodynamic environment associated with the Clymene Ocean closure, with the occurrence of a transition from accumulated cratonic-origin sediments over a passive margin to a predominated magmatic, metamorphic and deformational phase between 550 to 500 Ma.

Recently, sedimentologic and provenance studies of rocks from two geological formations of Alto Paraguay Group (Paraguay Belt) showed that their evolutions are associated with the Clymene Ocean closure (Bandeira *et al.* 2012, McGee *et al.* 2012, 2015a, 2015b). According to these studies, the top unit of Alto Paraguay Group represents the last transgressive deposits of the Paraguay Basin, resulting from the last stage of marine incursion of this ocean. Meanwhile, pelitic and fine sandstone deposits of Diamantino Formation (Upper Formation from Paraguay Group) are associated with the molassic phase. U-Pb detrital zircons dating of rocks from the basal part of this formation indicates that the deposition of Diamantino Formation occurred after 541 ± 7 Ma (Bandeira *et al.* 2012, McGee *et al.* 2012, 2015a, 2015b). Furthermore, the recent sedimentological and radiometric studies of glaciogenic rocks from Serra Azul Formation (Alto Paraguay Group) indicate that they are probably associated with the 580 Ma Gaskiers event (McGee *et al.* 2013, 2015a). These findings also propose an Ediacaran-Early Cambrian closure of the Clymene Ocean. The age of 518 ± 4 Ma (U-Pb zircon) obtained for the post-tectonic São Vicente Granite (Almeida & Mantovani 1975; McGee *et al.* 2012) establish the minimal age of the deformation and metamorphic phase in the northern part of Paraguay Belt and, therefore, the final time of the South America accretion in the Gondwana continent.

In a recent paper, however, Ganade de Araújo *et al.* (2014) discuss that the Goiás-Pharusian ocean separating the Amazonian-West African block from the proto-West Gondwana (also named as Central African block by Cordani *et al.* 2013a) closed beween 900 and 600 Ma. According to Ganade de Araújo *et al.* (2014), Himalaya-type mountains more than 2500 km long formed along this mega-suture (the Transbrasiliano-Kandy tectonic corridor, Cordani *et al.* 2013b), thus producing eclogitic rocks at about 130 km depth in the lithosphere, whose exhumation occurred at about 615 Ma. Unfortunately, paleomagnetic data between 900 and 600 Ma are rare for all Gondwana cratonic blocks, which make the tectonic processes involving Rodínia break-up and Gondwana formation undefiened.

## FINAL REMARKS

In the last decade, a significant increase of the Amazonian paleomagnetic data brought important implications for the geodynamic evolution of the Amazonian Craton and for its participation in supercontinents, mainly in Paleo to Mesoprotezoic times.

The Surumu Group pole corroborated the idea of a ca. 2000-1960 Ma pre-Columbia proto-Amazonian/West Africa link in a continental paleogeography, in which Guri (Guiana Shield) and Sassandra (West Africa Craton) shear zones were aligned. Similarly, the participation of the Amazonian Craton in the SAMBA model, forming the core of Columbia supercontinent, is constrained by the Avanavero pole, which is a model supported by geological and geochronological data (Johansson 2009). A paleogeography at 2000 Ma (Fig. 4) is also envisaged and comprises cratonic blocks that later on formed Laurentia, Baltica, and Amazonian/West Africa in the core of Columbia.

Paleo- to Mesoproterozoic paleomagnetic poles (Colíder, Nova Guarita, Indiavaí, and Salto do Céu poles) from southeastern Amazonian Craton (Brazil-Central Shield) suggest the occurrence of dextral strike-slip movements between the Guiana and the Brazil-Central Shields. These transcurrent movements could be due to the collision of the Paraguá Terrain with proto-Amazonia along the Alto Guaporé Belt at ca. 1320 Ma ago, although other tectonic events (Sunsás, Nova Brasilândia and Aguapeí orogens) may also be responsible for them. Another possible interpretation is that internal block rotations within Columbia supercontinent occurred between 1790 Ma (or 1530 Ma) and 1420 Ma ago (see Fig. 6).

The importance of Nova Guarita and Indiavaí poles should be highlighted for the significance of the E-W NBB whose origin resulted, most probably, of intracratonic reactivation that occurred during the collision of the Amazonian Craton with Laurentia along the Sunsás/Grenville Belt. Paleomagnetic data from late Mesoproterozoic and early Neoproterozoic are compatible with two scenarios for the collision of the Amazonian Craton with Laurentia in the formation of Rodínia: oblique collision, followed by relative transcurrent movement up to the collision of Amazonian Craton with Baltica at ca. 1000 Ma (Fig. 7), or starting from a SAMBA link, a clockwise rotation of Amazonia/West Africa Craton and Baltica with their final collision with Laurentia along the Grenville Belt (Fig. 8).

Finally, some geochronological and paleomagnetic data suggest that the collision of the Amazonian-West African Craton (plus Rio Apa block) with proto-Gondwana resulted in the formation of Gondwana only in the late Ediacaran and early Cambrian between 550 and 520 Ma. However, this hypothesis is contested by other geologic-geochronological evidence, which defend a prior (650-600 Ma) collision. We understand that only with more key paleomagnetic poles from Gondwana cratonic units in the interval between 900 and 550 Ma, we will be able to solve this issue.

## ACKNOWLEDGEMENTS

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