The Paleomagnetic Record of the São Francisco-Congo Craton

Chapter · December 2017

DOI: 10.1007/978-3-319-01715-0_16

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Abstract

This chapter, based on paleomagnetic and geologic-geochronological evidence, discusses the position of the São Francisco craton and other South American and African cratonic blocks within paleo-continents, since the formation of Columbia supercontinent in the Paleoproterozoic up to the fragmentation of Pangea in the Mesozoic. In Paleoproterozoic times, between ca. 2.0 and 1.8 Ga, two large independent landmasses were formed. The first one involved several cratonic blocks that were leading to the formation of Laurentia. Later, Laurentia, proto-Amazonia, West Africa and Baltica amalgamated to form the nucleus of the supercontinent Columbia at about 1.78 Ga. The second landmass encompassed the São Francisco-Congo, Kalahari, Rio de la Plata and Borborema-Trans-Sahara, forming the Central African block. For the São Francisco-Congo and Kalahari cratons, two robust Paleoproterozoic poles are available. One is from the Jequié charnockites of Bahia (São Francisco Craton), and the other from the Limpopo high-grade metamorphics in South Africa (Kalahari Craton). They support the possible link between these two cratonic blocks at ca. 2.0 Ga. Columbia may have remained united until 1.25 Ga, when Baltica and Amazonia/West Africa broke apart. Their paleomagnetic record seems to indicate that both executed clockwise rotations, until they collided with Laurentia along the Grenville belt at ca. 1.0 Ga., culminating with the formation of Rodinia. For the Central African block, however, there are no reliable paleomagnetic poles available between 1.78 and 1.27 MA. Nevertheless, during this time interval, the geological-geochronological evidence indicates that no continental collisional episodes affected the São Francisco-Congo craton, where important intra-plate tectonic episodes occurred. Most probably, this large continental block drifted alone since the end of the Paleoproterozoic and did not take part of Columbia or Rodinia. At the end of the Mesoproterozoic, ca. 1100 MA, the robust Umkondo pole of the Kalahari craton, as part of the Central African block, and the equally robust Keweenawan pole of Laurentia at the center of Rodinia, indicated that these landmasses were very far apart. At that time a large oceanic realm, the Goiás-Pharusian Ocean, was indeed separating Amazonia-West Africa from the Central African block. This ocean closed by a continued subduction process that started at ca. 900 MA and ended in a collisional belt with Himalayan-type mountains at ca. 615 MA, as part of the few continental collisions which formed Gondwana. However, the age of the final convergence is still a matter of debate,

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M. Heilbron et al. (eds.), *São Francisco Craton, Eastern Brazil*,
Regional Geology Reviews, DOI 10.1007/978-3-319-01715-0_16

because paleomagnetic measurements for the Araras Group, which occurs within the Paraguay belt at the eastern margin of the Amazonian craton, would indicate that a large ocean was still in existence between it and São Francisco craton close to the Ediacaran/Cambrian boundary. Consensus about this matter awaits for further paleomagnetic data. Gondwana collided with Laurasia during the late Paleozoic, at about 300 Ma, originating Pangea, which not much later started splitting apart, near the Permian/Triassic boundary. As part of this present-time plate tectonic regime, the São Francisco Craton (in South America) started separation from the Congo craton (in Africa) in Jurassic times, giving rise of the present-day oceanic lithosphere of the Atlantic Ocean.

Keywords
São Francisco Craton • Paleomagnetism • Supercontinents

16.1 Introduction

The physical link of the São Francisco craton in South America with the Congo craton in Africa prior to the opening of the South Atlantic ocean, is well established since the works by Martin (1961), Hurley et al. (1967), Almeida and Black (1968), Smith and Hallam (1970) among many others. The main purpose of this chapter is to review the available evidence from paleomagnetic measurements of the wandering of the São Francisco-Congo craton since its amalgamation in the Paleoproterozoic until its breakup during the development of the South Atlantic Ocean in the Lower Cretaceous. In this way, we will try to interpret its possible paleogeographic positions in relation to other companion cratonic masses in a few windows of the geologic time. Our time-slices (Figs. 16.1, 16.2, 16.3, 16.4 and 16.5) were chosen in order to correspond roughly to the reconstructions of supercontinents, which are envisaged to have been in existence since about 2000 Ma, namely, Columbia (Nuna), Rodinia, Gondwana and Pangea.

The paleogeographic reconstructions proposed here are largely based on geological correlations. However, the relative positions of the continental masses for each of the selected time-slices are determined by the available paleomagnetic data.

In paleomagnetism, the model used for paleogeographic reconstructions is the Geocentric Axial Dipole (GAD) Field. The GAD establishes that the mean geomagnetic field over some thousands of years (>10,000 years) averages out its secular variation and it may be represented by the field of a dipole at the center of the Earth, and disposed along the Earth's rotation axis.

If the Earth's geomagnetic field, at least since Paleoproterozoic times, behaved as the GAD model, and if the rocks collected at several sampled sites of a geological unit fully registered the geomagnetic secular variation, the mean inclination (Im) of the magnetic field preserved in the rocks can be obtained and the paleolatitude (λ) of the investigated continental block may be calculated by the expression: $\mathrm{tg}(\lambda) = 2\,\mathrm{tg}\,(\mathrm{Im})$. Moreover, the mean declination (Dm) of the magnetic field, also preserved in the rocks, will give the rotation of the same continental block, i.e., its paleomeridian.

Due to symmetry of the GAD Field, paleolongitude cannot be constrained. Therefore, the position of a continental block based on a single paleomagnetic pole could occupy any position along the same geographic parallel. In addition, another ambiguity related with paleomagnetic poles is the uncertainty on polarity (south or north pole?), which implies that two positions of the continental block are possible, in the northern hemisphere or in the southern hemisphere, after rotation of 180° (see Buchan et al. 2000). Finally, there is always some uncertainty about the age of the primary magnetization. These are the main weaknesses of reconstructions based on paleomagnetic measurements only, and therefore paleomagnetism could only provide support to paleogeographic models based on geological evidence, such as lithostratigraphic, tectonic or geochronological correlations. The paleomagnetic poles we used for the scenarios prior to the agglutination of Columbia up to the formation of Pangea in the Phanerozoic are presented on Table 16.1.

16.2 The São Francisco Craton Paleomagnetic Data Set

The paleomagnetic dataset available for the São Francisco craton (SFC) is very limited and the reconstructions made in this work were only possible by making use of the assumption that the SFC was united with the Congo Craton at least since Paleoproterozoic times.

For the SFC we have only two paleomagnetic poles from presumed Paleoproterozoic rocks: (*i*) the Jequié pole, obtained for the high-grade metamorphic rocks from the Jequié Complex, whose magnetization age was interpreted to be of ca. 2.02 Ga (D'Agrella-Filho et al. 2011), and (*ii*) the Uauá pole, obtained for dykes from the Uauá mafic dyke swarm, situated

Table 16.1 Selected paleomagnetic poles used in reconstruction of Figs. 16.1, 16.2, 16.3 and 16.4

Continent/formation	Plat (°N)	Plong (°E)	A_{95} (°) dp/dm	Age (Ma)	Ref.
Laurentia					
1. Minto dykes (Superior craton)	30	183	13	1998 ± 2	1
2. Mackenzie dykes	04	190	05	1267 ± 2	2
3. Upper Bylot.	08	205	04	1204 ± 22	2
4. Abitibi dykes	43	208	14	1141 ± 1	2
5. Logan sills	49	220	04	1109 + 4 − 2	3
6. Halliburton intrusives	−33	143	06	980 ± 10	4
7. Tsezotene sills and dykes	2	138	5	779 ± 2	3
8. Wyoming dykes	13	131	4	785 ± 8; 782 ± 8	3
9. Mean of 7 and 8 (780 Ma)	08	135		785	5
10. Kwagunt Formation	18	166	7	742 ± 6	3
11. Long Range dykes	19	355	15/21	615	6
12. Cloud Mountain Basalt	−5	352	2/4	615	6
13. Garnish red sandstones	−5	328		607	7
14. Famine Back Cove basalt	1	342		607	7
15. Mean of 10, 11, 12 and 13 (610 Ma)	3	344		610	5
16. Skinner Cove Fm.	−16	338	7/11	550 ± 3	8
17. Tapeats sandstones	−5	338	3	508	4
Baltica					
18. Pudozhgora Intrusion	64	149	11/14	1984 ± 8	9
19. Hakefjorden intrusives	−05	069	04	916 ± 11	10
20. Mean 550 Ma	−42	116		550	11
21. Tornetrask Fm.	56	116	12/15	535	4
Amazonian craton					
22. Oyapok granitoids and volcanics	−28	346	14	2020 ± 4	12
23. Avanavero sills and dykes	−48	28	10	1789	13
24. Nova Floresta Fm.	25	165	06	1198 ± 3; 1201 ± 3	2
25. Fortuna Fm.	60	156	10	1149 ± 7	14
Kalahari					
26. Vredfort mean	23	042	10/16	2023 ± 4	15
27. Limpopo metamorphics	26	22	08	1950 − 1980?	16
28. Premier Mine Kinberlite	51	038	07	1200	17
29. Premier combined	41	055	16	1150	17
30. Unkondo combined	64	−36	04	1105 ± 2	17
31. Namaqua metamorphics	08	330	11	1000 ± 20	17
Congo/São Francisco					
32. Jequié metamorphic complex	−01	343	10	~2020	18
33. Post-Kibaran Intrusives	17	293	07	1250	17
34. Bahia coastal A-normal	−14	288	07	923 ± 3	10
35. Gagwe Lavas	29	103	13	790	17
36. Mbozi Mafic Complex	46	325	9	750	17

(continued)

Table 16.1 (continued)

Continent/formation	Plat (°N)	Plong (°E)	A_{95} (°) dp/dm	Age (Ma)	Ref.
Rio de la Plata					
37. Florida dykes	−78	162	10	1790 ± 5	19
Arabia-Nubia					
38. Sinyai metadolerites	−29	319	5	547 ± 4	17
Brasiliano belt					
39. Itabaiana dykes	35	315	7	525 ± 5	20

Plat, pole latitude; Plong, pole longitude; A95, dp, dm—Fisher's statistic parameters. References: 1. Mitchell et al. (2014); 2. Tohver et al. (2002); 3. Li et al. (2008); 4. Meert and Torsvik (2003); 5. This work; 6. Lubnina et al. (2014); 7. Piper (2010); 8. McCausland et al. (2011); 9. Lubnina et al. (2016); 10. Evans et al. (2016); 11. Klein et al. (2015); 12. Nomade et al. (2003); 13. Bispo-Santos et al (2014b); 14. D'Agrella-Filho et al. (2008); 15. Salminen et al. (2009); 16. Morgan (1985); 17. Tohver et al. (2006); 18. D'Agrella-Filho et al. (2011); 19. Teixeira et al. (2013); 20. Trindade et al. (2006)

in northern Bahia state (D'Agrella-Filho and Pacca 1998). These authors attributed an age between 1.90 and 2.00 Ga for the magnetization age recorded by the rocks, based on a few Rb-Sr and K-Ar ages obtained for the dykes. However, recent U-Pb dating on baddeleyite and zircon grains of some noritic and tholeiitic dykes from the Uauá region yielded precise Archean ages of about 2720 Ma (Oliveira et al. 2013).

A group of paleomagnetic poles were obtained for unmetamorphosed mafic dykes from Ilhéus, Olivença and Itaju do Colônia regions in Bahia State (D'Agrella-Filho et al. 1990), and also for the coeval unmetamorphosed Salvador mafic dykes (D'Agrella-Filho et al. 2004). Precise ^{40}Ar/^{39}Ar dating on biotite and plagioclase of two dykes from Olivença and Ilhéus yielded ages of 1.08 Ma and 1.01 Ga, respectively (Renne et al.1990), and a biotite from a granulite at the contact with a 30 m thick Salvador dyke yielded an age of 1.02 Ga (D'Agrella-Filho et al. 2004). These paleomagnetic poles were taken as defining an apparent polar wander (APW) path for the SFC between 1.08 and 1.01 Ga (D'Agrella-Filho et al. 2004). However, recent U-Pb dating on baddeleyite and zircon of several dykes from the same swarms yielded precise ages systematically around 924 Ma (Evans et al. 2016), putting serious doubts on the previous Ar-Ar data.

Rather less reliable Neoproterozoic paleomagnetic poles (with reliability factor $Q \leq 3$) were obtained for some dykes near Itabuna (Bahia state), with an age about 780 Ma, and for a few other dykes near Lavras-Pará de Minas (Minas Gerais state), whose age is yet poorly constrained (Tohver et al. 2006). Finally, two magnetic components were disclosed for the Neoproterozoic carbonates of the Bambuí Group in Minas Gerais (D'Agrella-Filho et al. 2000), and the Salitre Formation in Bahia (Trindade et al. 2004). These components were interpreted as due to remagnetization processes occurred at ca. 520 Ma, under the thermal influence of the the Brasiliano (Pan-African) orogeny.

16.3 São Francisco Craton in Pre-Columbia Times

Prior to the formation of the Columbia/Nuna supercontinent at about 1.8 Ga, any reconstruction must be considered very speculative because the cratonic masses that may have contributed to its formation, such as Laurentia, Baltica, Central Amazonia, West Africa, Congo/São Francisco, and Kalahari were yet in the process of assembling.

The better known amalgamation process is that of Laurentia. It was only assembled at ca. 1.85–1.80 Ga after several continental collisions (Mitchell et al. 2014; ST-Onge et al. 2009). According to Mitchell et al. (2014), the Archean Slave and Rae blocks collided at 1.97 Ga, Slave/Rae and Hearne blocks collided at 1.92 Ga, and this latter block collided with the Superior craton at 1.85 Ga. These authors, based on paleomagnetic poles from the Slave and Superior cratons for the interval 2.2 and 2.0 Ga, demonstrated that the mentioned blocks were separated by a very large ocean (Manikewan ocean) at 2.0 Ga. Using Mitchell et al. (2014)'s reconstruction, we attempted to draw a possible paleogeographic reconstruction at 2.0 Ga (Fig. 16.1). In this figure, the paleogeographic position of the Superior craton is established using the 1998 Ma pole determined for the Minto dykes (number 1 in Table 16.1) from this Craton. The relative positions of the Superior (Su) and Slave (S) cratons are the same proposed by Mitchell et al. (2014), and the Hae and Hearne blocks were tentatively plotted between both cratonic blocks. At that time, Baltica was not formed as well. Karelia and Kola Archean areas, originally separated from the Volgo-Uralia and Sarmatia cratonic blocks (Bogdanova et al. 2013), collided at about 1.9 Ga (Daly et al. 2006). In Fig. 16.1, Karelia position was constrained by the Pudozhgora Intrusion pole (number 18 in Table 16.1), and Kola craton is positioned close to Karelia. According to Daly et al. (2006), these two cratons were linked, forming the Archean

Kenorland supercontinent (Pesonen et al. 2003). After 2.5 Ga, with the break-up of this supercontinent, a Wilson cycle developed with separation of Karelia and Kola cratons. This was followed by the formation of an ocean and its later closure along the Lapland-Kola orogen which ended at ca. 1.9 Ga.

According to Bogdanova et al. (2013), the collision between Sarmatia and Volgo-Uralia occurred between 2.1 and 2.0 Ga, producing the Volgo-Sarmatia block. Also, around 2.0 Ga, Central Amazonia and West Africa were probably already formed and together, following the collision of Archean blocks along the 2.25–2.05 Ga Maroni-Itacaiunas and Birimian orogenic belts (Cordani and Teixeira 2007). In Fig. 16.1, we envisage that a large landmass was composed by Volgo-Sarmatia plus Central Amazonia and West Africa, amalgamated along Paleoproterozoic orogenic belts. This model follows the so-called SAMBA connection of Johansson (2009), who proposed that, at ∼1.83 Ga, the nucleus of Columbia would include proto-Amazonia, West Africa and Baltica. The position of this landmass (Volgo-Sarmatia/Central Amazonia/West Africa) is constrained by the Oyapok granitoids pole (number 22 in Table 16.1) with an age of 2020 ± 4 Ma (see Nomade et al. 2003; Théveniaut et al. 2006 and D'Agrella-Filho et al. 2011). As shown on Fig. 16.1, subduction zones may have been active at the northern and western margins of Volgo-Sarmatia and Central Amazonia, respectively.

Fig. 16.1 Reconstruction at 2.0 Ga partially based on paleomagnetic data (modified from D'Agrella-Filho et al. 2016). The Superior craton (Su) was constrained using the Minto dykes pole (number 1 in Table 16.1). The relative positions of the Superior (Su) and Slave (S) cratons are the same proposed by Mitchell et al. (2014). Rae (R) and Hearne (H) cratonic fragments were tentatively positioned between Superior and Slave. The Karelia (KAR) craton was constrained using the Pudozhgora Intrusion pole (number 18 in Table 16.1). The Kola (K) craton is positioned close, but apart from Karelia, since it collided with this craton only at ca. 1.9 Ga (Daly et al. 2006). Proto-Amazonia (PAm) was constrained using the Oyapok Granitoids pole (pole 22 in Table 16.1). It is suggested that a large land mass composed by Proto-Amazonia (PAm), West Africa (WA), Volgo-Uralia (V-U) and Sarmatia (SA) was already in existence at that time. The Central African block, as defined by Cordani et al. (2013a) and forming a coherent mass composed by the Congo/São Francisco (CSF), Kalahari (KAL), Rio de la Plata (RP) and Borborema/Trans-Sahara (BTS), was constrained using the Vredfort mean pole (pole 26 in Table 16.1). The link between Proto-Amazonia and West Africa was made according to Bispo-Santos et al. (2014b). Dashed lines indicate later borders of Laurentia, Baltica and Amazonian craton. See text for details

Finally, a large continental block in Fig. 16.1 was probably formed at about 2.0 Ga. It was called Central African Block by Cordani et al. (2013a), when describing the process of amalgamation of Gondwana. Only a few poles, whose ages are not well-constrained, are actually available (D'Agrella-Filho et al. 2011), and can be used to support a close location of the São-Francisco-Congo and Kalahari paleocontinents at the core of the Central African Block. The other units of the block, the Borborema-Transahara, Rio de La Plata and Paranapanema, are considered in this work to have been part of the same unit because they include important areas made up of terrains in which Paleoproterozoic ages predominate.

The best paleomagnetic pole for the São Francisco craton, with Paleoproterozoic age, was obtained for the Jequié charnockites (number 32 in Table 16.1), whose granulite metamorphism was imposed between 2.1 and 2.0 Ga (Silva et al. 2002). However, a slightly younger age of magnetization is suggested for the Jequié pole based on ^{40}Ar/^{39}Ar ages (D'Agrella-Filho et al. 2011). It plots close to the Limpopo metamorphics "A" pole (Morgan 1985, pole 27 in Table 16.1) and to the well-dated 2023 ± 4 Ma mean pole (number 26 in Table 16.1) determined for rocks of the Vredefort impact structure (Salminen et al. 2009)—both from the Kalahari craton—in a pre-drift Gondwana configuration (D'Agrella-Filho et al. 2011). The Limpopo belt is interpreted to have resulted from the collision of the Kaapvaal and Zimbabwe cratons at Paleoproterozoic times where high-grade metamorphism was imposed at ca. 2.03–2.01 Ga (e.g., Buick et al. 2006). These facts imply that the São Francisco-Congo and Kalahari cratons could have been united in the Paleoproterozoic.

The Central African block, which contains the São Francisco-Congo and the adjacent cratonic units, is constrained in Fig. 16.1 by the Jequié pole (number 32 in Table 16.1), whose age is around 2.02–2.00 Ga. As we will argue repeatedly in this work (Figs. 16.2, 16.3 and 16.4), this continental block will probably keep its individuality until the end of the Neoproterozoic.

16.4 São Francisco-Congo Out of Columbia?

According to Rogers and Santosh (2009), the Columbia (Nuna) supercontinent mostly assembled by about 1.90–1.85 Ga, as suggested by geologic correlations, age constraints and other lines of evidence. Mainly due to the scarcity of key palomagnetic poles, different paleogeographic scenarios for Columbia have been proposed (e.g., Zhao et al. 2002; Pesonen et al. 2012; Pisarevsky et al. 2014, and references therein). Moreover, some authors postulated that it was not fully formed until 1.6 Ga ago (Evans 2013; Pisarevsky et al. 2014; Pehrsson et al. 2016).

In Fig. 16.2 the relative positions of Laurentia, Baltica, proto-Amazonia and West Africa were constrained according to the model by Bispo-Santos et al. (2014a). Starting with the paleogeographic reconstruction for 2.0 Ga shown on Fig. 16.1, an oblique collision occurred between the proto-Amazonia/West-Africa/Volgo-Sarmatia continental block with Fennoscandian terranes along the NW part of Sarmatia between 1.83 and 1.80 Ga (Bogdanova et al. 2013). According to these authors, after that collision, Volgo/Sarmatia (together with Central Amazonia and West Africa in our reconstruction) performed a counterclockwise rotation, which activated older strike-slip faults, which accommodated mafic dyke swarms with ages between 1.79 and 1.75 Ga in the Ukrainian Shield, northwestern Sarmatia. At about the same time (1.79–1.78 Ga) the widespread Avanavero mafic intrusions occurred as dykes and sills in Venezuela, French Guyana and northern Brazil (Reis et al. 2013). After Columbia formation at about 1.78 Ga (Fig. 16.2, see also Bispo-Santos et al. 2014a) minor internal rotations occurred associated with 1.75 Ga mafic dyke intrusions in the Ukrainian Shield (Bogdanova et al. 2013).

Fig. 16.2 Paleogeography of Columbia at 1.78 Ga. Laurentia (LAU), Baltica (BA), Proto-Amazonia (PAm) and West Africa (WA) were plotted as in Bispo-Santos et al. (2014a). Siberia (SI), Mawson continent (MC—South Australia plus East Antarctica), North Australia (NAu), West Australia (WAu), North China (NC) and India (IN) were plotted as in Xu et al. (2014). In this interpretation, the Central African block (RP Rio de la Plata, KAL Kalahari, CSF São Francisco/Congo, and BTS Borborema/Trans-Sahara block), constrained by the 1790 Ma Florida mafic dykes (number 37 pole of Table 16.1), formed a large continental mass, which could be close to Columbia, but probably did not belong to this supercontinent

In our view, after 1.78–1.75 Ga, a great continental mass composed by proto-Amazonia, West Africa, Baltica, and Laurentia may have formed the nucleus of the Columbia supercontinent, which probably remained united until 1.26 Ga ago (see Evans 2013 and references therein for further discussion). Other cratonic blocks could be included in the paleogeography of Columbia (Fig. 16.2, see also Xu et al. 2014). Siberia is positioned at the present northern Artic coast of North America according to Li and Evans (2011). Proto-Australia (Evans and Mitchell 2011), together with North China and India, were located close to North America, according to Xu et al. (2014). In the paleogeography shown on Fig. 16.2, Laurentia, together with all the cratonic blocks described above was rotated 64.6° clockwise around the Euler pole at 16.8°N, 323.6°E (Bispo-Santos et al. 2014a).

The relation of other African and South American cratonic blocks with Columbia is still undefined. As already mentioned, the Proterozoic paleomagnetic database for the São Francisco-Congo craton, especially in the Paleo- and Mesoproterozoic, is very poor. In our Fig. 16.2, the Rio de la Plata and Borborema/Trans-Sahara blocks were united to the São Francisco-Congo/Kalahari continent, forming the Central African block of Cordani et al. (2013a). We tentatively constrained the position of this large landmass at 1.78 Ga using the paleomagnetic pole obtained for the Florida dykes (number 37 in Table 16.1) from the Rio de la Plata craton (Teixeira et al. 2013).

If other parts of South America and Africa, such as Rio de La Plata and Kalahari, were accreted to the Central African block, and also if this large block took part of the Columbia supercontinent is still very uncertain. Recently, Cederberg et al. (2016) published some U-Pb baddeleyite ages for the Pará de Minas mafic dyke swarm from southern São Francisco craton. Their geochronological study revealed three episodes of dyke intrusions. The oldest of them was dated at 1790 Ma. In our Fig. 16.2, a closer position of the São Francisco-Congo craton relative to Siberia and North China (as suggested by Cederberg et al. 2016) would be permitted by the data, due to the longitude indefinition in paleomagnetism. However, if the Central African block was already formed at that time, some cratonic blocks would be superposed with parts of Columbia at 1790 Ma.

16.5 From Columbia to Rodinia

Taking into account the discussion above, we have tentatively proposed that the Central African block, composed by Congo/São Francisco/Kalahari/Borborema/Trans-Sahara/Rio de la Plata (and probably other smaller cratonic blocks hidden below the Phanerozoic Paraná basin, such as the Paranapanema block), was not part of Columbia. As demonstrated by Cruz and Alkmim (this book) and Alkmim et al. (this book) the tectonic evolution of the São Francisco craton between the end of Paleoproterozoic—when Columbia was still assembling-, and during the whole Mesoproterzoic Era, is marked by a series of intra-plate events associated with the formation of rift basins. No late Paleoproterozoic or Mesoproterozoic collisional events have been documented in the SFC yet. In our view, this large cratonic unit behaved as an individual continental block up to the formation of Gondwana in Ediacaran/Cambrian times, not linked to the Columbia supercontinent.

As already mentioned, no reliable paleomagnetic pole is available for this continental block between 1780 and 1270 Ma, so that we cannot trace its drift from the end of the Paleoproterozoic through most of the Mesoproterozoic. Figure 16.3 shows how we tentatively envisage the paleogeographic reconstructions from 1270 Ma to 920 Ma, and the possible path of the Central African landmass.

At around 1270 Ma, the nucleus of Columbia (Laurentia/Baltica/Amazonia/West Africa) was probably still united (Salminen and Pesonen 2007; Evans 2013). Its position on Fig. 16.3a is constrained by the Mackenzie dykes paleomagnetic pole (number 2 in Table 16.1) from Laurentia (Irving et al. 1972). These igneous rocks are considered to be part of a giant radiating 1267 Ma dyke swarm (Hou et al. 2008). The same figure indicates the possible position of the Central African block, constrained by the post-Kibaran paleomagnetic pole (number 33 in Table 16.1) obtained for the Congo craton (Meert et al. 1994) at 1250 Ma. Later, at about 1200 Ma (Fig. 16.3b), Baltica and Amazonia/West Africa broke up and separated from Columbia, performing a clockwise rotation up to their final collision with Laurentia to form Rodinia (see Evans 2013; Johansson 2014).

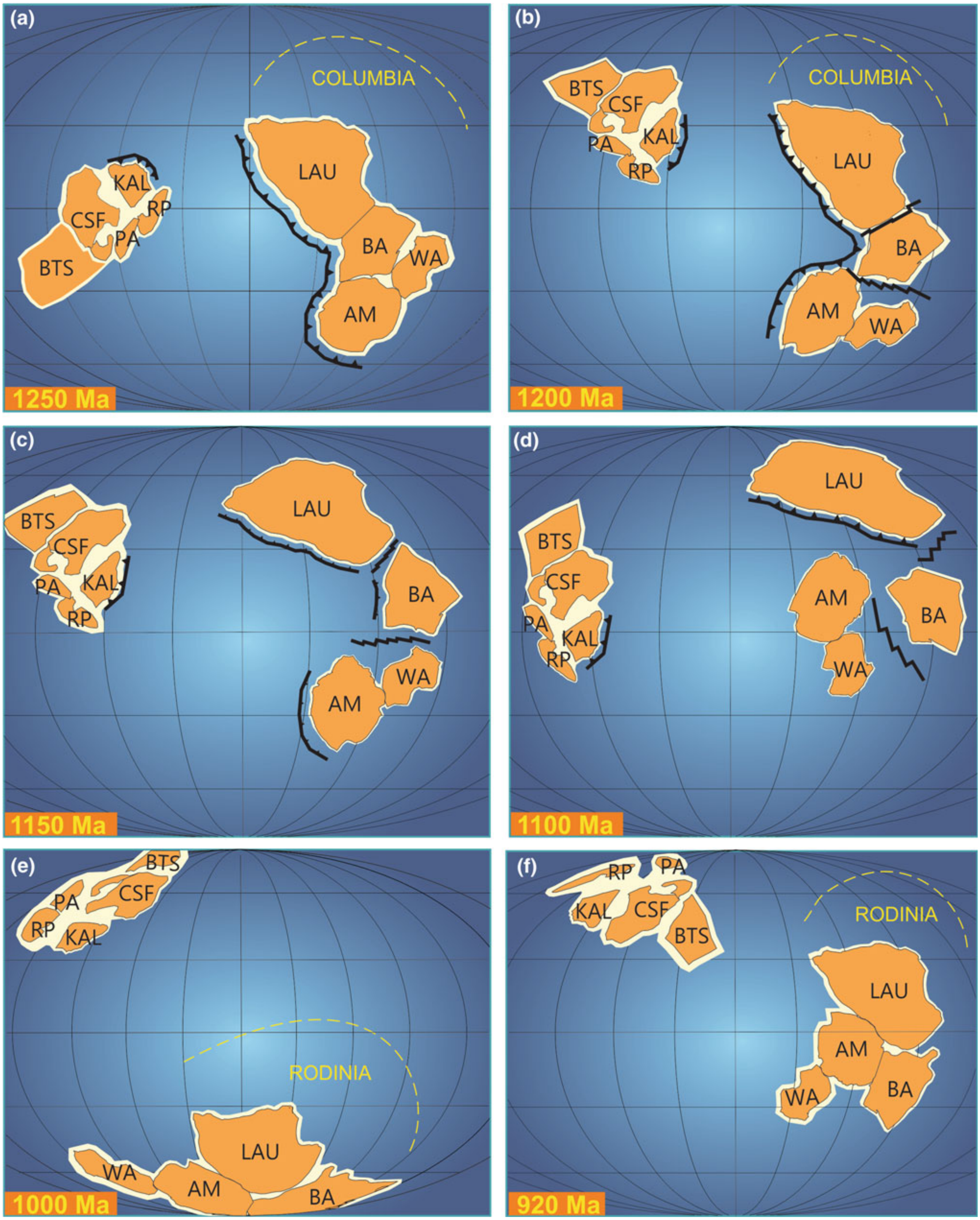
Tentative paleogeographic reconstructions for 1200, 1150, 1100 and 1000 Ma are shown on Fig. 16.3b–e, based on the available paleomagnetic poles included in Table 16.1. They illustrate possible scenarios since the initial rupture of the nucleus of Columbia up to the final assembly of Rodinia. In our view, the Central African block did not take part of Columbia or Rodinia, as discussed in the next section.

As indicated on Fig. 16.3, a large subduction system was active along the Kalahari margin of the Central African block. Accretion along this system led to the development of the Namaqua-Natal orogenic belt by the end of the Mesoproterozoic. This belt was interpreted by De Beer and Meyer (1984) as an Andean-type orogen characterized by abundant arc-related calc-alkaline magmatism, low-P high-T metamorphism, and a major contribution of mantle derived melts. Two decades later, Eglington (2006) confirmed the accretionary character of the orogen, which is actually made up predominantly of juvenile crust with minor contribution from older continental sources. The ages of the dominant mafic to intermediate igneous units fall between 1.2 and 1.3 Ga, whereas the granitic intrusions define two main magmatic events dated at 1.15 and 1.08–1.03 Ga.

The positions of Kalahari and Laurentia on Fig. 16.3d (1100 Ma) were constrained, respectively, by the very well-dated Unkondo pole (combined pole, number 30 in Table 16.1) and Logan dykes pole (number 5 in Table 16.1) from the Keweenawan magmatic event. The coeval Unkondo and Keweenawan magmatic events led some authors (Hanson et al. 1998) to propose that they would be distinct parts of the same large igneous province (LIP), and that Kalahari would be connected to Laurentia. However, paleomagnetic poles of the same age from both magmatic events yielded paleolatitudes that differ for more than 30°, precluding a direct connection between them (Dalziel et al. 2000; Pisarevsky et al. 2003; Meert and Torsvik 2003). Moreover, the same geomagnetic polarity was obtained for coeval Unkondo and Keweenawan rocks, which eliminates polarity ambiguity (Hanson et al. 2004). So, this fact constrains the orientation of Kalahari relative to Laurentia as shown in Fig. 16.3d. In this figure,

Fig. 16.3 Paleogeographic reconstructions at 1250 Ma (**a**), 1200 Ma (**b**), 1150 Ma (**c**), 1100 Ma (**d**), 1000 Ma (**e**) and 920 Ma (**f**), based on paleomagnetic data (modified from D'Agrella-Filho et al. 2016). Laurentia (LAU) was constrained by poles 3, 4 and 5 (Table 16.1) for 1200 Ma (**b**), 1150 Ma (**c**) and 1100 Ma (**d**), respectively. Amazonia (AM) was constrained by poles 24 and 25 (Table 16.1) for 1200 and 1150 Ma, respectively. The Central African block, which includes the Paranapanema craton (PA) since at least 1250 Ma, was positioned out of Columbia and also out of Rodinia, and was constrained using the following poles (Table 16.1): 33 for 1250 Ma; 28 for 1200 Ma; 29 for 1150 Ma; 30 for 1100 Ma, 31 for 1000 Ma and 34 for 920 Ma. The sequence of diagrams illustrates our interpretation for the fragmentation of the nucleus of Columbia and the formation of Rodinia, as also suggested by other authors (e.g. Evans 2013 and references therein). The nucleus of Columbia, including Laurentia (LAU), Baltica (BA), Amazonia (AM) and West Africa (WA), remained united since 1780 Ma (Fig. 16.2) up to 1260–1250 Ma (Fig. 16.3a). Its position at 1250 Ma was constrained by pole 2 (MacEnzie dykes, Table 16.1). After that time (Fig. 16.3b, e), Baltica and Amazonia-West Africa executed a clockwise rotation and finally collided again with Laurentia in a different position to form Rodinia at ca. 1000 Ma (Li et al. 2008). Pole 6 in Table 16.1 was used to constrain this large continental mass at 1000 Ma (Fig. 16.3e) and pole 19 (Table 16.1) was used to constrain it at 920 Ma (Fig. 16.3f)

▶


(a)
COLUMBIA
KAL
RP
CSF
PA
BTS
LAU
BA
WA
AM
1250 Ma
(b)
COLUMBIA
BTS
CSF
PA
KAL
RP
LAU
BA
AM
WA
1200 Ma
(c)
BTS
CSF
PA
KAL
RP
LAU
BA
WA
AM
1150 Ma
(d)
LAU
BTS
CSF
PA
KAL
RP
AM
BA
WA
1100 Ma
(e)
BTS
PA
CSF
RP
KAL
RODINIA
LAU
WA
AM
BA
1000 Ma
(f)
RP
PA
KAL
CSF
BTS
RODINIA
LAU
AM
WA
BA
920 Ma

Kalahari is plotted well far from Laurentia, although a closer approximation would also be permitted due to longitude indefinition in paleomagnetism.

At 1000 Ma (Fig. 16.3e), the position of the Central African block was constrained by the ca. 1000 Ma Namaqua pole (number 31 in Table 16.1) from the Kalahari craton (Renne et al. 1990). Laurentia plus Amazonia, West Africa and Baltica, appear in this figure as in the Rodinia reconstruction of Li et al. (2008), fixed by the 980 Ma Halliburton intrusions pole (number 6 in Table 16.1) (Buchan et al. 1983; Berger et al. 1979). Looking at the successive time-slices of Fig. 16.3, we note that, while Laurentia executed only a small (about 30° in latitude) movement to the northern hemisphere between 1250 Ma and 1100 Ma, the Central African block performed a clockwise rotation of almost 180° in the same time interval. In addition, between 1100 and 1000 Ma these continental blocks would proceed to opposite high latitudes.

Finally, at 920 Ma (Fig. 16.3f) the key paleomagnetic pole (number 34 in Table 16.1), obtained for the "normal" polarity mean directions disclosed for the Salvador, Olivença and Ilhéus dykes (Evans et al. 2016), was used to constrain the position of the Central African block. For this time, only Baltica has a reliable paleomagnetic pole (number 19 in Table 16.1), which was used to fix in Fig. 16.3f the Laurentia/Amazonia/West Africa/ Baltica continental mass, which would return to an equatorial position.

16.6 Was São Francisco-Congo Out of Rodinia?

Several attempts to correlate the São Francisco-Congo craton to the Mesoproterozoic Rodinia Supercontinent have been made (see Evans 2013 and references therein). First, D'Agrella-Filho et al. (1990) and Renne et al. (1990), based on the paleomagnetic poles and ^{40}Ar/^{39}Ar ages at that time available for the Ilhéus, Olivença and Itaju do Colônia mafic dykes (northern SFC, see Girardi et al. this book) suggested an APW path for this cratonic unit between 1.08 and 1.01 Ga. A comparison of the obtained APW path with those traced for Laurentia and Baltica for the same time interval, led D'Agrella-Filho et al. (1998) and Weil et al. (1998) to propose a Rodinian paleogeography, in which the São Francisco-Congo (together with Kalahari) faced Laurentia along the southern Llano Grenvillian orogenic belt at ca. 1000 Ma. In this reconstruction the Amazonian craton also faced Laurentia along the Sunsás and Grenville belts, in a position close to the São Francisco-Congo craton. A similar reconstruction was proposed by Li et al. (2008), based on the same paleomagnetic poles. An alternative paleomagnetically-based reconstruction for Rodinia was later suggested by Evans (2009), in which the São Francisco-Congo was linked to northern Laurentia.

Based on geological and geochronologial evidence, Kröner and Cordani (2003), Cordani et al. (2003) and Pisarevsky et al. (2003) suggested that the São Francisco-Congo and Kalahari cratons did not take part of Rodinia. The main reason was that a large ocean existed between Amazonia and Congo-São Francisco at about 940 Ma ago, a fact supported by juvenile intraoceanic magmatism recorded all along the present-day central Brazil (Pimentel et al. 1999). D'Agrella-Filho et al. (2004) used the same reasoning to re-interpret the paleomagnetic and the age data for the Salvador mafic dykes. A plateau ^{40}Ar–^{39}Ar age (biotite) of 1021 ± 8 Ma was obtained for a granulite at the contact of one of the Salvador dykes, helping to establish the APW path of the Congo-São Francisco craton between 1.08 and 1.01 Ga. These authors proposed then three different configurations for Rodinia, all of them considering the São Francisco-Congo craton (and Kalahari) located quite far from the core of Rodinia, an interpretation also adopted by Tohver et al. (2006).

However, as already mentioned in Sect. 16.2, new U-Pb age determinations on baddeleyite and zircon from the Salvador, Ilhéus and Olivença dykes yielded systematically younger ages, close to 920 Ma, which were interpreted as the time of the intrusions (Evans et al. 2016), casting doubts on the previous Ar-Ar datings. New paleomagnetic results obtained on the same dykes by these authors replicate the previous results published by D'Agrella-Filho et al. (1990, 2004). From the old and new paleomagnetic data, Evans et al. (2016) calculated new means using site mean directions for both, "normal" and "reverse" polarities: Dec = 86.5°, Inc = −72.3° ($N = 33$, $\alpha_{95} = 4.1°$, $K = 38$), and Dec = 299.9°, Inc. = 62.1°, ($N = 13$, $\alpha_{95} = 5.9°$, $K = 51$), which yielded the following paleomagnetic poles: 288.3°E, 14.3°S ($A_{95} = 6.8°$) and 282.0°E, 10.2°N, respectively ($A_{95} = 8.5°$). Unfortunately, all the U-Pb 920 Ma ages are from dykes with "normal" polarity, so that no U-Pb age is presently available for the "reverse" directions that could constrain the age of the related pole described above. Therefore, the pole number 34 in Table 16.1 is the only key paleomagnetic pole dated at 920 Ma for the São Francisco-Congo craton that can be used to constrain the paleogeography of this unit in respect to the Rodinia supercontinent.

For the age interval of 935–910 Ma, Baltica is the only cratonic block for which reliable paleomagntic poles are presently available (Pisarevsky and Bylund 2006). Using these poles and the 920 Ma key paleomagnetic pole for the São Francisco-Congo craton described above, Evans et al. (2016) tested two configurations proposed for Rodinia by Li et al. (2008) and Evans (2009). None of them pass the test.

Other possible configurations of the São Francisco-Congo relative to Baltica/Laurentia are also possible, such as those proposed by Cawood and Pisarevsky (2006). For example, São Francisco-Congo could be linked to the western or southwestern Laurentia (with North America in its present position), or to the present northeastern or southeastern Baltica (see Evans et al. 2016). Following Kröner and Cordani (2003), Cordani et al. (2003), Pisarevsky et al. (2003), D'Agrella-Filho et al. (2004) and Tohver et al. (2006), we suggest that São Francisco-Congo was not part of Rodinia at 920 Ma ago, as shown on Fig. 16.3f.

16.7 São Francisco-Congo in Gondwana and Pangea

The dispersal of Rodinia and the wandering followed by collision of its fragments gave rise to the Gondwana continent, which was only completely amalgamated in Cambrian times (Meert and Van der Voo 1997). However, the time when Amazonia plus West Africa broke-up from Rodinia, as well as the time they finally collided with the Central African block are yet in dispute.

On geological-tectonic grounds, Ganade de Araujo et al. (2014) demonstrated that a large oceanic realm, the Goias-Pharusian ocean, once separated Amazonia-West-Africa from the Central African block. Closure of this ocean involved a continued subduction process from about 900 up to 600 Ma, giving rise to Himalaya-type mountains. The related suture, exhumed at around 615 Ma, is more than 2500 km long and marked by eclogitic rocks formed at depths of about 130 km.

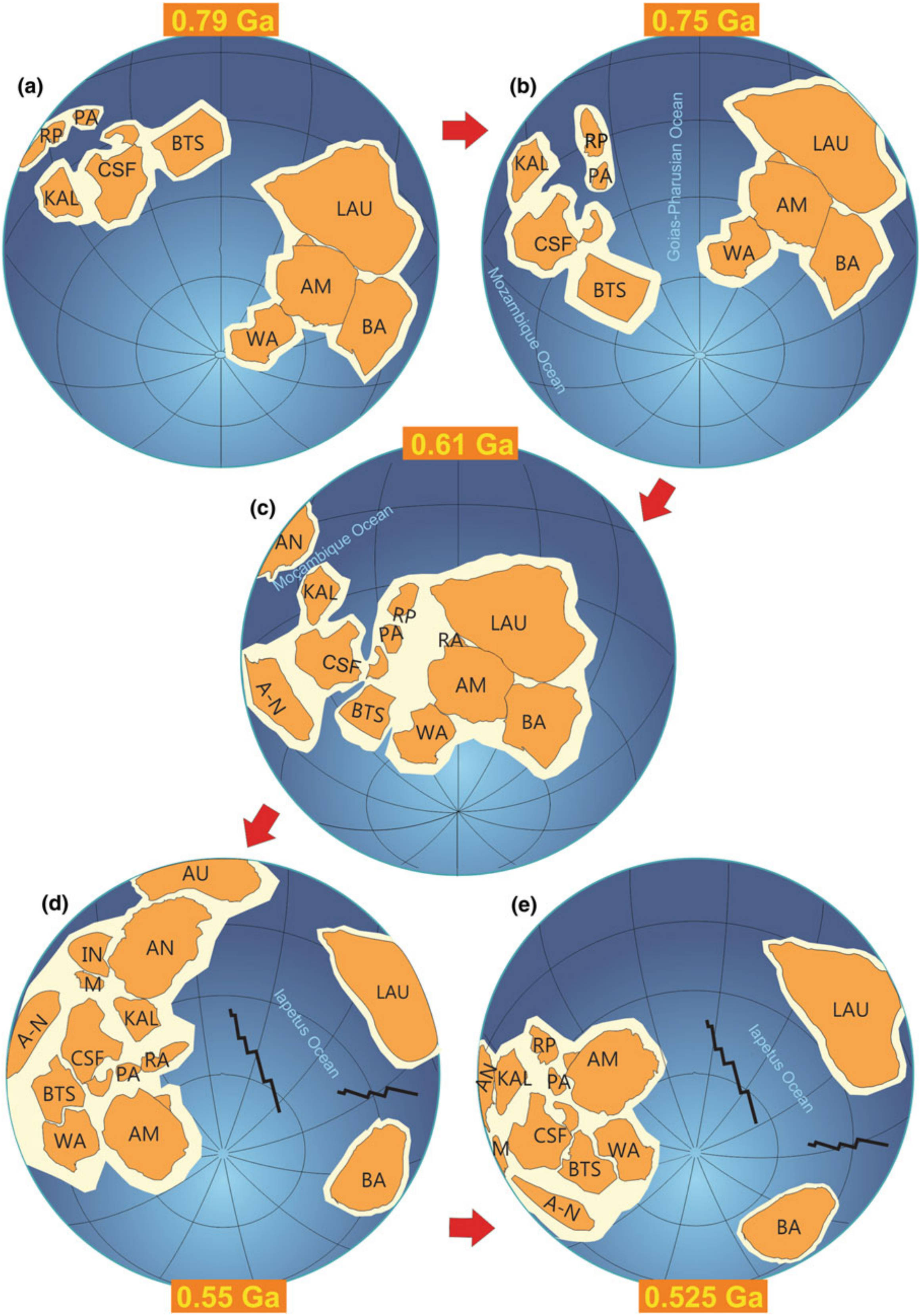
Trindade et al. (2006), interpreting paleomagnetic data from the Araras Group of the Paraguay belt in central Brazil, concluded that a large Ediacaran ocean (named by them as the Clymene ocean) separated Amazonia from the São Francisco-Congo craton. According to these authors closure of the Clymene took place only during Cambrian (550–520 Ma). However, the directions disclosed for the Araras Group, although registering both polarities along a sedimentary profile (Trindade et al. 2003), are close to the present geomagnetic field, which puts some doubt about their primary origin (Pisarevsky et al. 2008). More recently, Tohver et al. (2010) proposed that folding, trusting and remagnetization of carbonates occurring along the oroclinal inflection of the Paraguay belt dated at 528 ± 36 Ma caused the coherent change in declination observed in the remanent magnetization disclosed for the rocks collected in the northern and southern segments of the orocline, reflecting thus the closure of the Clymene ocean at Cambrian times.

These disputing hypotheses gave rise of an interesting debate (see discussions in Cordani et al. 2013b, 2014 and Tohver and Trindade 2014). The main argument of Cordani et al. (2013b), although recognizing the existence of a major seaway like the Clymene in South America, is that it should have been not an ocean, but a large epicontinental sea, formed over the pre-existent continental crust of West Gondwana. Indeed, many authors advocate a final collision between Amazonia plus West Africa against the Central African block at around 650–600 Ma, after the closure of the great Goiás-Pharusian ocean along the Transbrasiliano-Kandi megashear (e.g., Trompette 1994; Cordani et al. 2000, 2013b; Ganade de Araujo et al. 2014; Cordani et al., this book, among many others).

Figure 16.4 shows a possible scenario for the formation of Gondwana considering the hypothesis that at 650–600 Ma the large Goias-Pharusian ocean that once separated São Francisco-Congo- and Amazonia was already closed. At 790 Ma and 750 Ma (Fig. 16.4a, b), Central Africa and Laurentia/Amazonia/West Africa/Baltica (and probably other cratonic blocks that formed Rodinia, see Li et al. 2008) behaved as independent entities. At 610 Ma, given that West Gondwana was already formed, the paleogeographic reconstruction shown on Fig. 16.4c was constrained by the mean of ca. 610 Ma paleomagnetic poles from Laurentia (number 15 in Table 16.1). After 600 Ma, Baltica and Laurentia broke-up from West Gondwana forming the Iapetus Ocean as shown on Fig. 16.4d and Fig. 16.4e, for at 550 Ma and

Fig. 16.4 Paleogeographic reconstructions at 790 Ma (**a**), 750 Ma (**b**), 610 Ma (**c**), 550 Ma (**d**) and 525 Ma (**e**), based on paleomagnetic data. The sequence of diagrams shows the formation of Gondwana, with the closure of the Goiás-Pharusian and Mozambique oceans, and the separation of Laurentia (LAU) and Baltica (BA), with the opening of the Iapetus Ocean. For 790 Ma, the Gagwe lavas pole (number 35 in Table 16.1) from the Congo craton, and the mean pole (number 9 in Table 16.1) calculated for Laurentia (785 Ma) were used for the reconstruction. For 750 Ma, the reconstruction was made using the Mbozi Complex pole (number 36 in Table 16.1) from the Congo craton and Kwagunt Formation pole (number 10 in Table 16.1) from Laurentia. Between 750 Ma and 610 Ma there is a lack of paleomagnetic control for the different cratonic fragments. A mean pole (number 15 in Table 16.1) was used for Laurentia to constrain the block formed by Laurentia/Amazonia/West Africa/Baltica at 610 Ma. Moreover, we also suppose that West Gondwana was practically formed at that time. For 550 Ma, the Sinyai metadolerites pole (number 38 in Table 16.1) from Arabia-Nubia (A-N) block was used to constrain West Gondwana position, the Skinner Cove Formation pole (number 16 in Table 16.1) was used for Laurentia and a mean pole (number 20 in Table 16.1) was used for Baltica. At this age, the Iapetus Ocean is wide open and the Gondwana supercontinent is practically formed, with the amalgamation of India (IN), Madagascar (M), Antarctica (AN) and Australia (AU), and the Central African block occupying its nucleus. Finally, for 525 Ma, the Itabaiana dykes pole (number 39 in Table 16.1) was used to constrain West Gondwana, Tapeats Formation pole (number 17 in Table 16.1) for Laurentia and Tornetrask Formation pole (number 21 in Table 16.1) for Baltica

▶


0.79 Ga
(a)
RP
PA
BTS
CSF
KAL
LAU
AM
WA
BA
0.75 Ga
(b)
KAL
RP
PA
Goias-Pharusian Ocean
LAU
AM
CSF
WA
BA
BTS
Mozambique Ocean
0.61 Ga
(c)
AN
Moçambique Ocean
KAL
RP
PA
RA
LAU
CSF
A-N
AM
BTS
WA
BA
(d)
AU
AN
IN
M
A-N
KAL
CSF
RA
PA
BTS
WA
AM
lapetus Ocean
LAU
BA
0.55 Ga
(e)
RP
AM
A-N
KAL
PA
CSF
M
WA
BTS
A-N
lapetus Ocean
LAU
BA
0.525 Ga

525 Ma, respectively (see also Cawood et al. 2001 and Klein et al. 2015).

In any case, new paleomagnetic data for the 900–600 Ma interval is required for all Gondwana cratonic blocks. Figure 16.5 shows one of the many configurations adopted for the Gondwana continent (Schmitt et al. 2008). The Central African block, as shown by this figure, includes the São Francisco-Congo craton in its nucleus. In the late Paleozoic, Gondwana collided with Laurentia and other continental fragments forming Pangea, a supercontinent that encompassed all continental masses existing on Earth at that time (see Domeier et al. 2012 for a comprehensive discussion on this matter).

The evolution of the São Francisco-Congo craton during the Phanerozoic is well known. It remained as part of Gondwana during the formation of Pangea at about 300–280 Ma. During the rupture of Pangea, the São Francisco craton yet incorporated in South America and the Congo craton in Africa started to drift away from one another at ca. 130 Ma, as sea-floor spreading began in the young South Atlantic.

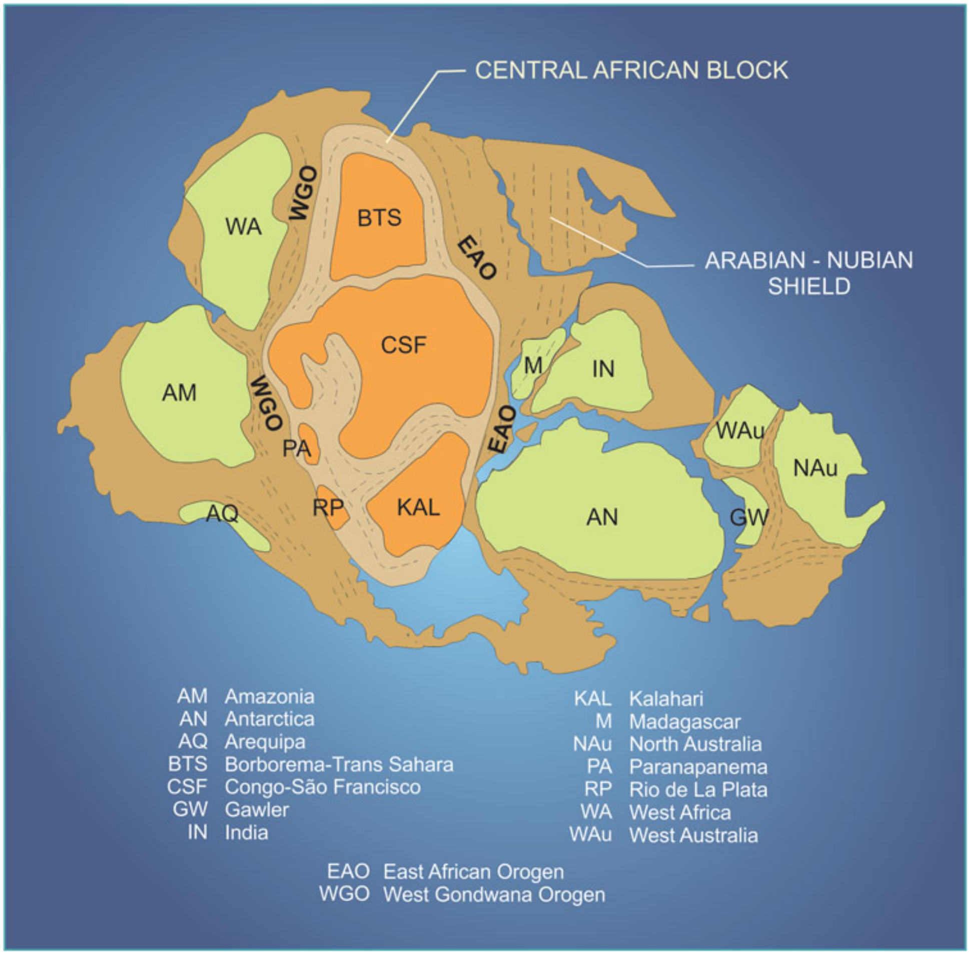


Fig. 16.5 Gondwana configuration adapted with some modifications from Schmitt et al. (2008). WA—West Africa; AM—Amazonia; AQ—Arequipa; BTS—Borborema-Trans-Sahara; CSF—Congo/São Francisco; KAL—Kalahari; PA—Paranapanema; RP—Rio de la Plata; M—Madagascar; IN—India; AN—Antarctica; WAu—West Australia; Nau—North Australia; GW—Gawler Craton. EAO—East African Orogen; WGO—West Gondwana Orogen

16.8 Conclusions

Based on geologic-geochronological and paleomagnetic evidence, this chapter discusses the trajectory of the São Francisco craton and other cratonic blocks from South America and Africa from ca. 2.1 Ga in the pre-Columbia Paleoproterozoic up to at ca. 300 Ma, as they become incorporated into Pangea. Our main conclusions are the following:

1. At 2.0 Ga at least two large landmasses with independent drifts are envisaged. The first involved proto-Amazonia, West Africa and Volgo-Sarmatia, which collided with the Kola-Karelia to form the nucleus of Columbia at ca. 1.78 Ga. The second, referred to as Central African block (Cordani et al. 2013a), encompassed São Francisco, Congo, Kalahari, Rio de la Plata and Borborema-Trans-Sahara.
2. The Central African block most likely did not take part of Columbia or Rodinia, drifting alone from 2.0 Ga until the formation of Gondwana at the Ediacaran/Cambrian boundary.
3. At 2.0 Ga, amalgamation of Laurentia was in progress. A large ocean (Manikewan Ocean) separated several cratonic blocks, such as the Superior, Rae, Hearne, Slave, and parts of Greenland and Baltica, which became completely agglutinated only at ca. 1.85–1.80 Ga ago.
4. The nucleus of Columbia, formed at ca. 1.78 Ga by the proto-Amazonia, West Africa, Baltica and Laurentia, remained united up to 1.25 Ga. After that, proto-Amazonia/West Africa and Baltica broke up and experienced a clockwise rotation until docking again with Laurentia along the Grenville belt and becoming incorporated into Rodinia at ca. 1000 Ma. During this time, the Central African block underwent a clockwise rotation, drifting from low to high northern latitudes.
5. The timing of the final assembly of West Gondwana is matter of debate. Some models propose a collision of Amazonian and São Francisco during closure of the Clymene ocean at the Edicaran/Cambrian boundary (550–530 Ma) (e.g., Tohver et al. 2010). Other authors (e.g., Ganade de Araujo et al. 2014) postulate an early collision of these cratonic blocks, which would occur during closure of the Goiás-Pharusian ocean at ca. 650 Ma. After that, Laurentia and Baltica broke apart, opening the Iapetus Ocean. At the same time other continental blocks (Antarctica, Australia and India) collided with the West African block to form Gondwana.
6. Gondwana remained as an integrated continental mass for more than 300 Ma. It collided with Laurasia at about 300–280 Ma, forming the Pangea, which started to split apart at around 180 Ma. With the opening of the South Atlantic at about 130 Ma, the São Francisco craton (in South America) and the Congo Craton (in Africa) drifted away from each other reaching their present positions.

Acknowledgments We thank Fernando F. Alkmim for its helpful comments on the text.

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