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Review

Wrapping a Craton: A Review of Neoproterozoic Fold Belts Surrounding the São Francisco Craton, Eastern Brazil

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Abstract: A synthesis of the evolution of the Neoproterozoic belts or orogens surrounding the São Francisco craton (SFC) in northeastern and southeastern Brazil is presented. Emphasis is placed on recognizing the superposition of sedimentary basins, from rift to passive margin to retroarc and foreland, as well as identifying three diachronic continental collisions in the formation of the SFC. The Tonian passive margin occurs in the southern Brasília Belt with the Vazante, Canastra, and Araxá Groups. During the Tonian, island magmatic arcs and basins developed in front and behind these arcs (fore- and back-arcs). Subsequently, in the Cryogenian–Ediacaran, a retroarc foreland basin developed with part of the Araxá Group and the Ibiá Group, and finally, a foreland basin developed, which was filled by the Bambuí Group. A tectonic structure of superimposed nappes, with subhorizontal $S_{1\text{–}2}$ foliation, formed between 650 and 610 Ma, is striking. In the northern Brasília Belt, there is the Stenian passive margin of the Paranoá Group, the Tonian intrusion of the Mafic–Ultramafic Complexes, and the Mara Rosa Island magmatic arc, active since the Tonian, with limited volcanic–sedimentary basins associated with the arc. A thrust–fold belt structure is prominent, with S1 foliation and late transcurrent, transpressive tectonics characterized by the Transbrasiliano (TB) lineament. The Cryogenian–Ediacaran collision between the Paranapanema and São Francisco cratons is the first collisional orogenic event to the west. In the Rio Preto belt, on the northwestern margin of the São Francisco craton, the Cryogenian–Ediacaran Canabravinha rift basin is prominent, with gravitational sediments that represent the intracontinental termination of the passive margin that occurs further northeast. The rift basin was intensely deformed at the Ediacaran–Cambrian boundary, as was the Bambuí Group. On the northern and northeastern margins of the São Francisco craton, the Riacho do Pontal and Sergipano orogens stand out, showing a comparable evolution with Tonian and Cryogenian rifts (Brejo Seco, Miaba, and Canindé); Cryogenian–Ediacaran passive margin, where the Monte Orebe ophiolite is located; and Cordilleran magmatic arcs, which developed between 620 and 610 Ma. In the Sergipano fold belt, with a better-preserved outer domain, gravitational sedimentation occurs with glacial influence. A continental collision between the SFC and the PEAL (Pernambuco-Alagoas Massif) occurred between 610 and 540 Ma, with intense deformation of nappes and thrusts, with vergence to the south and accommodation by dextral transcurrent shear zones, such as the Pernambuco Lineament (PE). The Araçuaí belt or orogen was formed at the southeastern limit of the SFC by a Tonian intracontinental rift, later superimposed by a Cryogenian–Ediacaran rift–passive margin of the Macaúbas Group, with gravitational sedimentation and glacial influence, and distally by oceanic crust. It is overlain by a retroarc basin with syn-orogenic sedimentation of the Salinas Formation, partly derived from the Rio Doce cordilleran magmatic arc and associated basins, such as the Rio Doce and Nova Venécia Groups. A third continental collision event (SF and Congo cratons), at the end of the Ediacaran (580–530 Ma), developed a thrust–fold belt that deforms the sediments of the Araçuaí Belt and penetrates the Paramirim Corridor, transitioning to the south to a dextral strike-slip shear zone that characterizes the Ribeira Belt.

Citation: Uhlein, A.; Uhlein, G.J.; Caxito, F.d.A.; Moura, S.A. Wrapping a Craton: A Review of Neoproterozoic Fold Belts Surrounding the São Francisco Craton, Eastern Brazil. *Minerals* **2024**, *14*, 43. https://doi.org/10.3390/min14010043

Academic Editors: Camille Rossignol, Francesco Narduzzi, Cristiano de Carvalho Lana and Michel Villeneuve

Received: 25 September 2023
Revised: 24 December 2023
Accepted: 27 December 2023
Published: 29 December 2023

Keywords: neoproterozoic orogens; São Francisco craton (SFC); neoproterozoic sedimentary basins; diachronic orogenic evolution; Brazil

1. Introduction

The São Francisco craton [1–4] and its continuation in Africa, the Congo Craton [5], constitute Archean–Paleoproterozoic paleocontinents which, via various continental collisions during the Neoproterozoic–Cambrian, formed the western portion of the Gondwana supercontinent [5]. The folded Brasiliano/Pan African belts occur on the margins of the paleocontinents in the form of several superimposed sedimentary basins, showing different types of magmatic arcs (accretionary material) and which, via collisional processes, were transformed into Neoproterozoic–Cambrian orogenic belts [1,3,4,6–9].

The São Francisco craton is surrounded by several orogenic belts, most notably the Brasília belt (to the west), the Rio Preto, Riacho do Pontal, and Sergipano belts (to the north), and the Araçuaí belt, which grades into the Ribeira belt (to the southeast; Figure 1). The boundaries between the São Francisco craton and the Neoproterozoic belts are generally transitional, indicated by increased orogenic deformation, with folds and thrust faults or nappes. The boundary is usually indicated by the first reverse fault affecting the cover and basement rocks [1,3,7,8].

The São Francisco craton comprises two stratigraphic units: 1—an Archean–Paleoproterozoic basement (gneisses, granitoids, greenstone belts, and supracrustal rocks older than 1.8 Ga) and 2—Sedimentary Proterozoic–Phanerozoic stratigraphic units, generally little deformed to horizontal [2,3,7,8].

The Neoproterozoic orogenic belts are made up of several superimposed, strongly deformed (thrust–fold belts) and metamorphosed stratigraphic units, ranging from greenschist to granulite facies. The stratigraphic units represent (1) Tonian and Cryogenian, rift to passive margin sedimentary basins, with slivers of ophiolitic rocks; (2) accretionary material (pre-collisional granitoids from intraoceanic and continental magmatic arcs); (3) sedimentary sequences derived from magmatic arcs; (4) syn- to post-collisional granitoids; and (5) tectonic occurrences of Archean–Paleoproterozoic basement (microcontinents) [4,7–9].

With the evolution of Brazil's geologic knowledge, especially the evolution of geological mapping and geochronological methods (U-Pb and Sm-Nd), it has been possible to recognize various sedimentary basins, magmatic arcs and reconstruct the evolution of the orogenic belts [4,10–12]. This is a summary of the evolution of the orogenic belts surrounding the São Francisco craton. The emphasis is on recognizing superimposed sedimentary basins, extensional events, and paleogeographic scenarios. A synthesis of the tectono-sedimentary evolution of the Neoproterozoic folded belts around the São Francisco craton is presented in this paper, which covers a large area in east–central Brazil (Figure 1) and is significant to the understanding of the West Gondwana supercontinent evolution.

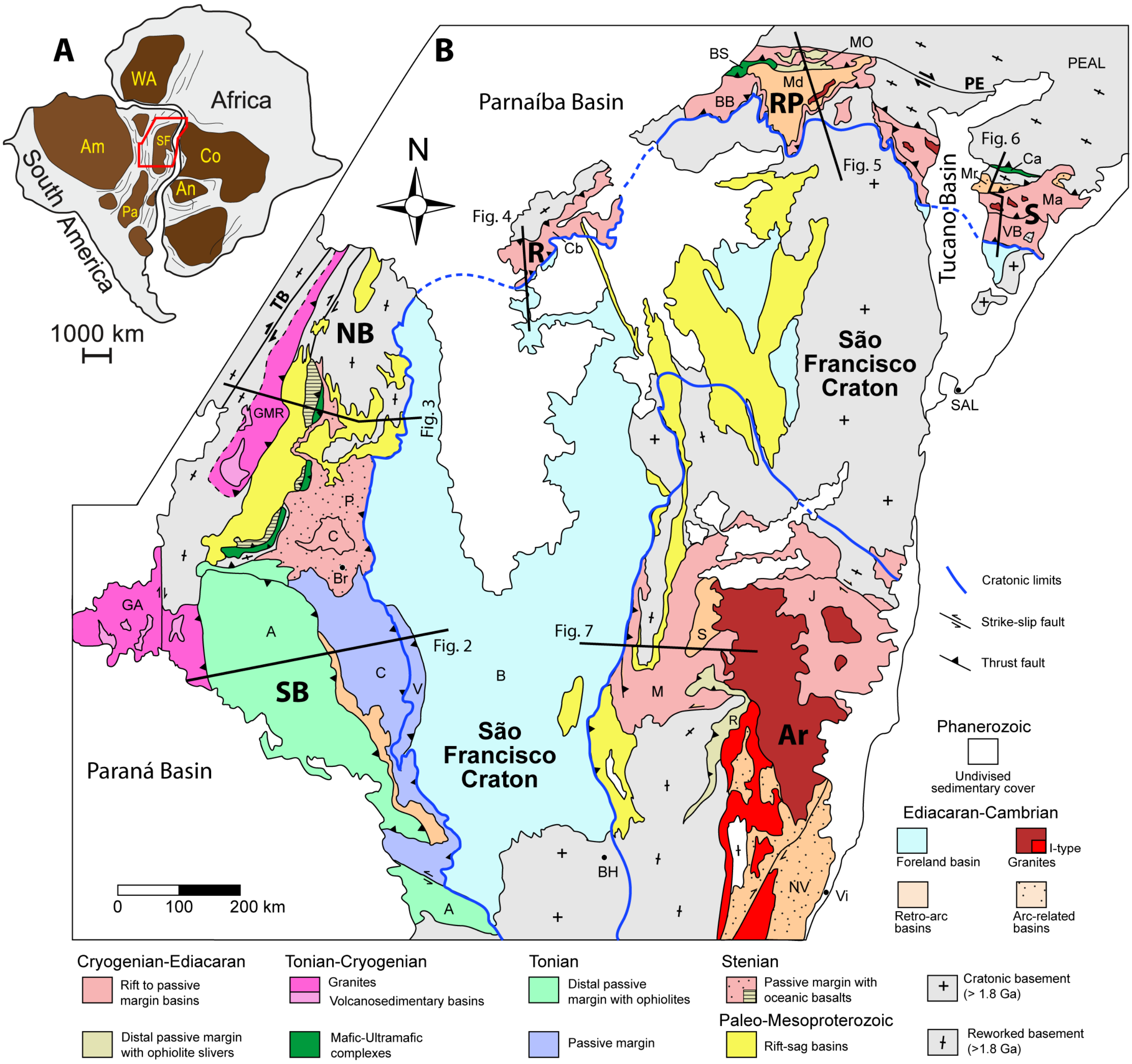

Figure 1. (**A**): The Western Gondwana supercontinent with Neoproterozoic orogens and cratons and location of (B). (**B**): The São Francisco craton and Neoproterozoic fold belts. Modified from [9]. The locations of the geologic sections from Figures 2–7 are indicated by black lines. Fold belts: SB—Southern Brasília; NB—Northern Brasília; R—Rio Preto; RP—Riacho do Pontal; S—Sergipano; Ar—Araçuaí. Stratigraphic units from the Southern Brasília fold belt: A: Araxá Group; C: Canastra Group; GA: Goiás/Arenópolis Magmatic Arc; I: Ibiá Group; V: Vazante Group. Stratigraphic units from the Northern Brasília fold belt: GMR: Goiás/Mara Rosa Magmatic Arc; P: Paranoá Group. Stratigraphic units from the Rio Preto fold belt: Cb: Canabravinha Formation. Stratigraphic units from the Riacho do Pontal fold belt: BB: Barra Bonita Formation; BS: Brejo Seco Complex; M: Mandacaru Formation, MO: Monte Orebe ophiolite. Domains from the Sergipano fold belt: C: Canindé Domain; Ma: Macururé Domain; Mr: Marancó Domain; PEAL: Maciço Pernambuco-Alagoas; VB: Vaza Barris Domain. Stratigraphic units from the Araçuaí fold belt: M: Macaúbas Group; J: Jequitinhonha Complex; NV: Nova Venécia Complex; R: Ribeirão da Folha Formation; S: Salinas Formation. Lineaments: PE: Pernambuco lineament; TB: TransBrasiliano lineament. Cities: BH—Belo Horizonte; Br—Brasília; SAL—Salvador; Vi—Vitória.

2. Southern Brasília Orogen

The Neoproterozoic fold–thrust Brasília orogen [1,13–15] is one of the main tectonic units in Central Brazil, a well-preserved Neoproterozoic orogenic belt within the Tocantins Province (Figure 1). The Brasília Belt can be subdivided into the northern and southern belts, which show important stratigraphic, tectonic, and geochronological differences [13–16]. In this paper, we will discuss the Brasília Belt as two independent orogens, where the Southern Brasília Belt was produced by the collision between the Paranapanema and São Francisco cratons, and the Northern Brasília Belt was produced by the collision between Amazonian and São Francisco cratons [15,17]. The southern Brasília orogen shows a tectonic interference zone with the Ribeira belt in the Socorro-Guaxupé nappe region [18,19] and extends northwest, making a bend and inflecting toward an E-W trend south of the Pirineus syntax [20].

The Southern Brasília orogen presents two structural domains: (1) an internal domain, with allochthon units (the upper nappe complex), prominent subhorizontal schistosity, and medium to high degree of metamorphism; and (2) an external domain, a typical fold–thrust belt, with subhorizontal foliation and an overall low degree of metamorphism (greenschist). Beyond the Brasília Belt, to the east, the cratonic domain occurs, characterized by the Ediacaran–Cambrian sedimentary cover of the Bambuí Group, with two subdomains: (1) a thin-skinned foreland fold–thrust belt; and (2) a central domain with subhorizontal layers [3]. The Southern Brasília Belt shows a predominance of Neoproterozoic passive margin units, with ophiolitic slivers, magmatic arcs, and syn-orogenic basins, now exposed along a fold–thrust system [14,15,18]. The passive margin of the Southern Brasília belt (Figure 2) is formed by the Vazante Group (lower unit—eastward), Canastra Group (middle unit), and Araxá Group (upper unit—westward).

The Vazante Group (250 km long and 25 km wide) occurs between the cratonic domain (Bambuí Group) on the east and the Southern Brasília external domain (Canastra-Ibiá thrust) on the west. It is composed of metapelites and stromatolite-bearing meta-dolomites [14] with a controverse age of sedimentation, either Stenian or, more probably, Tonian [21]. Hf data of detrital zircon indicate that sources were represented mainly by recycled Paleo-Mesoproterozoic crust of the São Francisco paleocontinent, suggesting a passive margin context [22]. Recently, Marques et al. [23,24] correlated conglomerates (diamictites) and pelites of the base of the Vazante Group to the Jequitaí Formation (Bambuí Group). The Paranoá Group outcrops locally, below the Bambuí Group, in the cratonic domain, near reverse faults [14,25,26].

The Canastra Group consists mainly of metasandstones, metapelites, and subordinate metacarbonate lenses, with a thickness of 3500–4500 m. In the Paracatu region (northwestern state of Minas Gerais), the Canastra Group represents a sedimentary regressive megacycle [14]. The lower part, consisting of metapelites rich in organic matter and pyrite, represents deep-water sediments, overlain by turbiditic metarythmites and quartzites with hummocky structures, suggesting offshore platform sediments. The youngest detrital zircons, dated at ca. 1.0 Ga, suggest a Neoproterozoic sedimentation age and a cratonic (SF Craton) provenance for this group [27–29].

The Araxá Group comprises metapelitic schists (with biotite and garnet) and paragneisses (with feldspar, quartz, and biotite), chlorite schists and amphibolites, quartzites, metabasic schists, and metaultramafic lenses, with amphibolite metamorphic grade [14]. Rock associations of oceanic affinity are present, with graphitic schists, calc-silicate rocks, and minor iron and manganese formations and metachert [27,30,31]. The Araxá Group shows turbiditic metarhythmites and lenticular quartzites, suggesting submarine fan sedimentation in the passive margin basin. The Araxá Group schists and paragneisses frequently contain lenses and pods of metabasic (chlorite schists and amphibolites) and metaultrabasic rocks (small lenses of serpentinite, amphibolite, and talc schist, with podiform chromite deposits) representing a long, roughly N-S trending ophiolitic mélange [32–34]. Amphibolites intercalated with the Araxá schists near the city of Goiânia have been dated at ca. 800 Ma (SHRIMP U-Pb zircon data [35]). The Araxá metasedimentary rocks present a bimodal pattern of Sm–Nd model ages, suggesting different source areas, one of which is related to the Neoproterozoic Goiás Magmatic Arc [36]. The interpretation has been corroborated by U-Pb age patterns of detrital zircon grains, which display an abundant Neoproterozoic population, with ages between ca. 900 (paleocontinent provenance) and 630 Ma (magmatic arc provenance) [15,36,37]. Recently, E-MORB amphibolitic rocks in the Araxá Group (Veríssimo sequence, see [38]) were characterized from an outcropping between Pires do Rio and Catalão, southern Goiás, aged 980 Ma, in addition to 780 Ma metabasalts from the syn-orogenic basin, probably characterizing a back-arc basin [38].Metagabbros from continental collision (650 Ma) can also be found. The Araxá Group (mica schists and quartzites) represents different metasedimentary rocks deposited at different times and in different environments (passive margin and arc-related basins) and were later superimposed tectonically.

The Anápolis–Itauçú Complex outcrops in a NW–SE elongated zone exposed between the Goiás Magmatic Arc and Araxá Group, southern Goiás state. The Complex consists of ortho- and paragranulites, with layered mafic–ultramafic rocks, locally presenting ultra-high-T mineral assemblages [16,39–42]. Geochronological data support the interpretation that at least part of the Anápolis–Itauçú Complex may represent high-grade equivalents of the Araxá Group in the metamorphic core of the Southern Brasília belt [16,41,42].

The Ibiá Group is composed of two units: the basal Cubatão Formation (metadiamictites with clasts of granite–gneiss, quartzites, schists or phyllites, and carbonate rocks) and the upper Rio Verde Formation (phyllites, metarythmites, and quartzites). The basal-diamictites have the youngest dated zircons at 935 $\pm$ 11 [28,29]. The upper Rio Verde Formation has the youngest grains dated at 636 $\pm$ 21 Ma [28], at 639 $\pm$ 15 [43], and at 580 Ma [37]. The Cubatão Formation in the Brasília Belt is correlated to the glacial Jequitaí Formation on the easterward São Francisco paleocontinent, featuring a transition between subaqueous gravitational sedimentation (debris flow) and marine glacial sedimentation to the east [7,24]. A regional glaciation (Marinoan glacial event [44]) developed in the São Francisco paleocontinent in the Cryogenian/Ediacaran transition (630 Ma), related to the glaciomarine sedimentation of the Jequitaí Formation. This unit also outcrops into the Brasília belt in the Cristalina dome (south of Goiás State). The Rio Verde Formation is interpreted as representing syn-orogenic sedimentation derived from the continental magmatic arc in a retroarc foreland basin [31,37,45].

The Goiás Magmatic Arc is one of the most important tectonic units of the Brasília Belt (Figure 2). The southern sector of the Goiás Magmatic arc is known as the Arenópolis arc [46–48]. Early evolution of the arc took place in Tonian intra-oceanic island arcs between ca. 930 and 810 Ma, with the crystallization of very primitive tholeiitic to calc-alkaline volcanics and associated tonalites/granodiorites [47–49]. The rocks display positive εNd(t) values and the Nd TDM model ages mostly between 0.8 and 1.1 Ga [46,47]. The intra-oceanic Arenópolis Island Arc was the first subduction-related orogen recorded by the accretion of juvenile calc-alcaline metatonalite bodies. It records a long-lived (250 Ma) plate convergence motion in a large oceanic basin. A younger cycle of magmatic activity took place between ca. 670 and 600 Ma [16,48,49]. This second cycle also comprises volcanic–sedimentary sequences, calc-alkaline tonalite–granodiorite intrusions, as well as bi-modal intrusions comprised of gabbro/diorite/granite. Sm-Nd data produced TDM values varying in a much wider range, from ca. 0.9 to 2.2 Ga, suggesting a higher contribution/contamination with older continental crust and indicating that this second event took place in a continental arc. Supracrustal volcano–sedimentary sequences of the Goiás Magmatic arc comprising calc-alkaline metavolcanic rocks, feldspar-bearing mica schist, and minor quartzites (e.g., the Arenópolis and Bom Jardim de Goiás sequences). It is noteworthy that there is a partial superposition of arc magmatic activity and collisional events, illustrating the geotectonic complexity of the southern Brasília fold belt. The Tonian volcanic–sedimentary Córrego do Santo Antônio unit (Arenópolis Sequence) comprises metamafic–ultramafic bodies with metachert and marble, mica-schists, and quartzites [50].

This Tonian Sequence is interpreted as a trench–forearc basin of the Arenópolis intra-oceanic magmatic arc [50].

A westward-dipping subduction zone is proposed to produce an intra-oceanic arc during the Tonian, with consumption of the small oceanic basin formed between the island arc and the paleocontinent (back-arc basin) (Figure 2). During the Tonian–Cryogenian, the island arc remnants were docked to the passive continental margin of the São Francisco paleocontinent [47,49]. As a result, subduction polarity reversal probably occurred, with the development of the Goiás continental arc (Arenópolis arc) in the Cryogenian–Ediacaran, by partial melting of the coupled continental margin and juvenile arc set at 670–600 Ma (Figure 2) [49].

In summary, the Southern Brasília orogen shows several overlapping sedimentary basins (Figure 2): (1) a Tonian passive margin (Araxá, Canastra, and Vazante Groups); (2) a Tonian fore and back intra-oceanic arc basins [33,38,50]; (3) a Cryogenian–Ediacaran retroarc foreland basin constituted by the Ibiá Group, part of the Araxá Group and Santo Antonio–Rocinha Formations (Vazante Group), with the lateral transition to the São Francisco paleocontinent [24,31,43,45]; see Figure 2. The Ibiá Group represents remnants of these early foreland deposits related to the uplift of Southern Brasília orogen, incorporated into the orogenic wedges due to the advance of the deformational fronts.

The Bambuí Group is the most important Ediacaran–Cambrian sedimentary unit in central Brazil, covering large areas of the São Francisco craton. Its basal glacial diamictite (Jequitaí Formation) sits unconformably on the Paranoá Group and Espinhaço Supergroup. The age of this glacial event is highly debated [44,51,52], and both Sturtian (~730–660 Ma), Marinoan (~635 Ma), or late Ediacaran ages have been proposed. At the southwestern edge of the Bambuí Group, in the state of Minas Gerais, conglomeratic sequences occur, such as the Samburá Formation to the south and the Lagoa Formosa Formation to the north. Both represent conglomeratic wedges that characterize the Bambuí Group as a foreland basin formed by the Brasília Southern Belt [14,53]. The expressive occurrence of late Ediacaran detrital zircons and fossil remnants from the middle portion of the Sete Lagoas Formation (Cloudina) and the Três Marias Formation (Treptichnus pedum) (uppermost portion of the Bambuí Group) corroborate a probable late Ediacaran to Cambrian age for much of the Bambuí Group [36,54–59]. Considering that the Bambuí Group is deformed along the craton margin, the recent age determinations indicate that several orogenic fronts must have been active up to Cambrian times.

The general structure of the Southern Brasília belt makes a bend with the concavity toward SW. It shows subhorizontal foliation (S1 and S2) and a structure of nappes and subhorizontal thrusts with displacements of great magnitudes [15,27,30]. In the external domain, with the metamorphism of the greenschist facies, quartzites of the Canastra Group form klippes over cratonic units, such as the Vazante and Bambuí Groups, with subhorizontal contacts. The upper nappes (in the internal domain) show paragenesis of amphibolite and (high-P) granulite facies and are mainly composed of rocks of the Araxá Group (metamorphic core). On the west, these nappes are in tectonic contact (thrust to the east) with the Goiás magmatic arc. The first and two (D1 and D2) deformation phases are syn-metamorphic, constitute progressive tangential deformation with thrusts and detachment surfaces toward the craton with subhorizontal surfaces S1 and S2 (main foliation, crenulation cleavage type), recumbent folds, and strong stretching lineation 270 to 300 Az [14,15,27,30]. Open and smooth folds with subvertical spaced cleavage S3 occur. The metamorphism is dated between 650 and 620 Ma [15,17–19]. Two distinct metamorphic stages were identified [60]: an arc-related metamorphism (670–640 Ma) and a continental collision to decompression involving partial melting (630–590 Ma). The magnitude of deformation and displacements of nappes increases toward the south, as seen in the Passos nappe that directly covers the Bambuí Group [27,61,62].

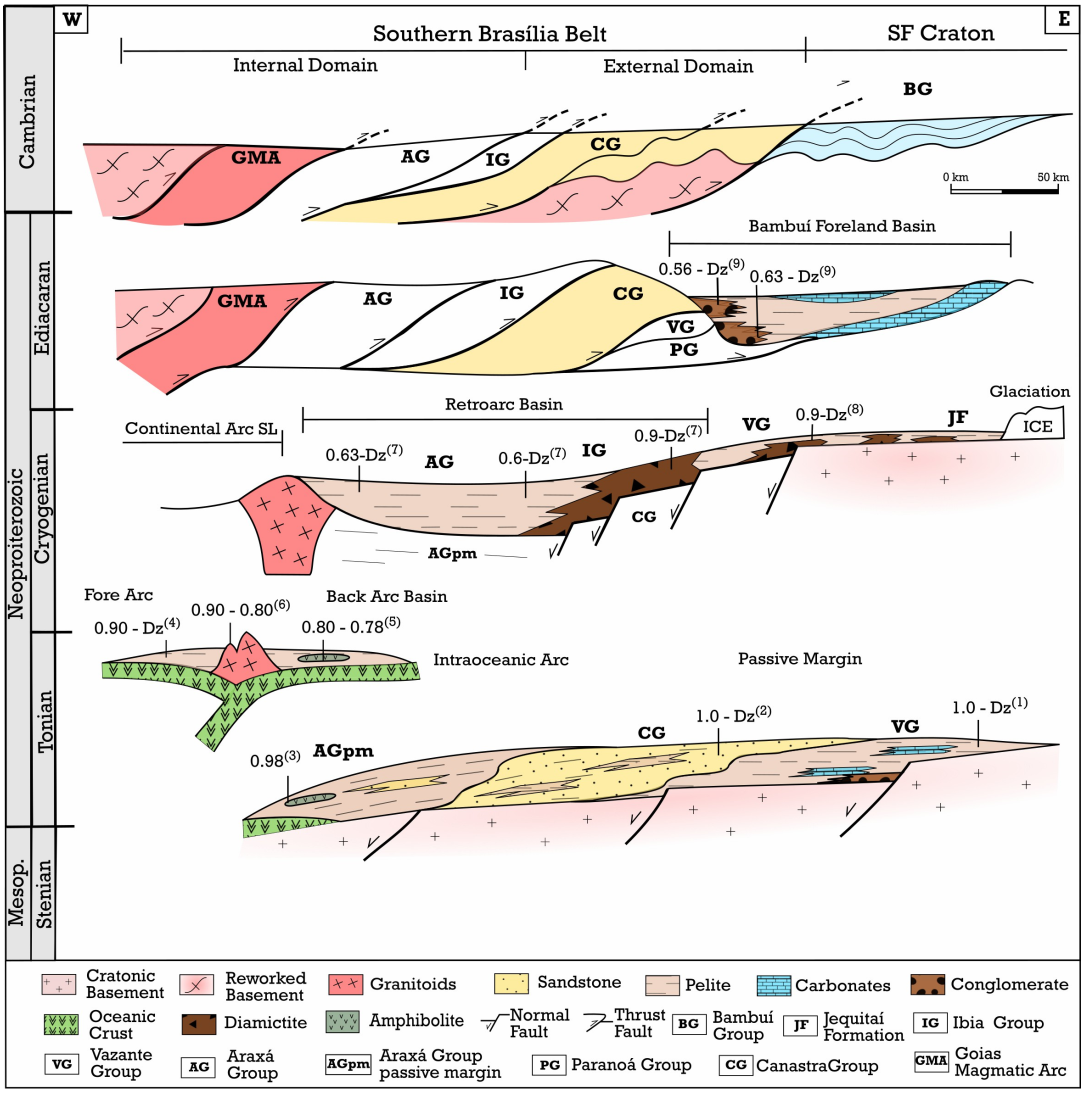

Figure 2. The Southern Brasília belt: sedimentary basins, extensional and contractional events, and geological evolution [14,15,17]. Geochronological data: 1—[21,22]; 2—[27,29]; 3—[38]; 4—[50]; 5—[33,35,38]; 6—[46–48]; 7—[28,36,37,43]; 8—[24]; 9—[53]. Dz: Detrital zircon.

3. The Northern Brasília Orogen

The southern limit of the Northern Brasília belt is the Pirineus syntaxis, where the structures are E-W oriented, verging south and gradually forming an arc to the north, which verges eastward to the São Francisco craton. The external zone of the Northern Brasília belt is a fold–thrust belt of low-grade paleo-mesoproterozoic metasedimentary rocks. The internal zone comprises syn-orogenic volcano–sedimentary sequences and calc-alkaline plutonic rocks related to the Goiás Magmatic Arc, the Goiás massif (a probably exotic Archean–Paleoproterozoic continental fragment), Neoproterozoic layered complexes, and Mesoproterozoic (Ectasian–Stenian) volcano–sedimentary sequences. (Figure 3). Neoproterozoic units in the Northern Brasília Belt occur locally and correspond to the magmatic arc of Mara Rosa and to the Mafic–Ultramafic Complexes [1,14,16,49,63,64].

In the Northern Brasília belt, Paleo-mesoproterozoic rocks predominate, overlapping different sedimentary basins. The Statherian Araí Rift is noteworthy, consisting of the Arraias Formation with thick alluvial quartzites and conglomerates deposited in a rift phase, with mechanical subsidence and intercalations of metavolcanic rocks (basalts, riolythes, agglomerates). An important first extensional phase, with the development of normal faults, must have occurred, associated with the Arraias Formation and A-type granitoids and acid-intermediate volcanic rocks [14,65,66]. The Calymmian Traíras Group represents an intracontinental sag-type basin separated from the Arraias rift basin by an unconformity [67]. The Traíras Group shows fine-grained quartzites, pelites, and lenses of limestones and dolomites [14]. The Serra da Mesa Group (1000–3000 m thick) corresponds to a succession of coarse quartzites (base) and fine-grained, laminated, muscovite-rich quartzites. In the upper part, mica schists mainly occur with minor quartzites and stromatolite-bearing marbles deposited in a marine shelf setting [14]. During the Calymmian, there was a transition from the Traíras Group to the Serra da Mesa Group in the same sag basin [66,67]. The Serra da Mesa and Traíras Groups have similar isotopic compositions (δ13C in carbonate rocks and Sm–Nd model ages) in both units, and detrital zircon U–Pb ages are between 2.4 and 1.55 Ga [66,67]. A younger generation of anorogenic tin-enriched granites (Rio Tocantins Sub-province) dated at 1.56 Ga [65,68] is related to a reactivation of a Calymmian rift-sag basin.

During the Ectasian–Stenian, another basin develops that is strongly asymmetrical, associated with an important extensional phase, filled by the sediments of the Paranoá Group. It consists of sandstones, pelites, rhythmites, and carbonate lenses with columnar stromatolites arranged in transgressive and regressive cycles [14,69,70]. The São Miguel conglomerate (basal) indicates an erosive unconformity between the Paranoá Group and the older Proterozoic basins. Available geochronological data for the Paranoá Group consists of detrital zircon U-Pb ages determining a maximum depositional age of 1560 ± 10 Ma and a diagenetic xenotime U-Pb age suggesting deposition at 1042 ± 22 Ma [71]. The 50 m thick São Miguel conglomerate represents the rift phase of the Paranoá basin [49,72]. It is overlain by marine rhythmites and sandstones deposited in a shelf environment dominated by tidal and storm currents [14,70]. The sediments in the upper portion of the Paranoá Group display features indicating more varied environments, reflecting important sea-level fluctuations: deeper water pelites alternate with rhythmites and quartzites, storm-influenced rhythmites, limestones, and stromatolitic dolomites [70]. The Arkose Level [73], in the upper Paranoá Group, represents a record of braided river deposits, probably associated with normal fault activity (Figure 3). The Paranoá basin is thicker to the west (4000–2500 m thick), with a decrease in quartzites and an increase in turbiditic metarythmites, suggesting a westward passive margin [14,49]. An increase in deformation and metamorphism is also shown toward the west, within the interior Brasília orogen. Recently, the Quilombo Formation from Paranoá Group was identified in the external Brasília belt [74]. This unit comprises metaturbidites (greywacke, siltstones, and shale) and metabasalt layers with ages of 1.39 Ga [74].

Three Meso-Neoproterozoic mafic–ultramafic layered complexes define a 350 km belt striking NNE-SSW along the central–northern part of the Northern Brasília Belt. The composite intrusions are known as the Canabrava, Niquelândia, and Barro Alto complexes, from north to south, e.g., [47,75–77]. The western part of the belt comprises sedimentary and volcanic rocks of the Juscelândia, Indaianópolis, and Palmeirópolis sequences and gabbro–anorthosite complexes of the Serra da Malacacheta and Serra dos Borges, formed in a rift environment that evolved to the ocean floor at ca. 1270 Ma. The volcano–sedimentary sequences of Palmeirópolis, Juscelândia, and Indaianópolis are made of bimodal metavolcanic rocks, metabasalt, metachert, and mica schists. The metabasalts have a MORB affinity, a U-Pb age of 1.2 Ga, and an extensional rifting context [47,49,75,77,78] and are probably the oceanic crust of the Paranoá passive margin (Figure 3). Toward the east, these volcano–sedimentary and plutonic rocks tectonically overlie the mafic–ultramafic layered complexes (UMC).

The Barro Alto, Niquelândia, and Canabrava mafic–ultramafic layered complexes (UMC) show a lower mafic zone (gabbro–norite), ultramafic zone (dunite–piroxenite) and an upper zone (gabbro–norite), affected by high-grade metamorphism at 780–760 Ma [47,63,76]. The crystallization age is 790–800 Ma and is related to the taphrogenesis processes from the Rodinia breakup [49,63,79,80]. The upper and lower zones of the Mafic–Ultramafic Complexes are interpreted as two unrelated intrusions of Meso and Neoproterozoic ages, respectively [76]. However, the authors of [81,82] do not recognize this model (two distinct igneous events at 1.3 Ga and at 790 Ma) and suggest that the three complexes were formed during a single magmatic event in the Neoproterozoic. They propose that the complexes represent fragments of the larger Tonian Goiás Stratiform Complex, which was intruded at the bottom of a continental crust at 770–800 Ma in a back-arc extensional setting [81,82].

The Goiás magmatic arc comprises two sectors, separated by the Archean terranes of the Goiás massif. The northern sector is the Mara Rosa arc [46,47,49,63]. Geochronological studies in the Goiás magmatic arc have shown an initial intraoceanic phase (0.89 to 0.85 Ga) and another terminal collisional phase (0.65 to 0.60 Ga) [83]. The Mara Rosa magmatic arc shows the evolution in two phases: (1) calc-alkaline tonalite–granodiorites that represent granitoids evolved in intra-oceanic arcs dated up to ca. 890–860 Ma and (2) more evolved granitoids and volcanic rocks, and bi-modal intrusions of gabbro, diorite, tonalite and granite dated at ca. 660 and 600 Ma, accompanied by metamorphism and deformation [16,49,83], which represent continental magmatic arcs (Andean type). εNd(t) values are more varied, and TDM model ages vary between 1.0 and 2.0 Ga, suggesting that this second phase of magmatic arc development took place in the presence of older continental crust, most likely in a continental arc setting. The long history of arc magmatism (900–600 Ma) suggests that the western margin of the São Francisco paleocontinent was a large oceanic basin where interoceanic island arcs were accreted.

The external domain of the Northern Brasília Belt shows important overthrust shear zones and folds toward SE separated by zones of weak deformation and metamorphism, preserving stratigraphic relationships between the Paleo-Mesoproterozoic basins. The tectonic structures make a SW-NE arc, with tectonic transport to SE. S1 schistosity is penetrative, associated with folds, thrust, and dextral ductile strike-slip faults (SW-NE). From west to east occur the large ductile dextral shear zones of the Transbrasiliano Lineament (TBL), interpreted as a suture zone [84], and the ductile thrust shear zone of the Rio Maranhão [85]. Eastward, the western ductile structures grade to the ductile–brittle shear zones of the Alto Paraíso–Cavalcante system, with reverse faults and thrusts [62,85]. These reverse faults limit and cut rigid, slightly deformed paleo-mesoproterozoic blocks, showing large open folds, cushioning the impact of the Transbrasiliano system [62,86]. Regional metamorphism increases westward, from the greenschist facies near the cratonic border to the amphibolite and granulite facies to the west in the metamorphic core [42,80,87].

The two segments of the Brasília Belt represent the result of a diachronic continental collision. It started in the southern sector (collision of Paranapanema with São Francisco cratons, ca. 650–610 Ma), with subhorizontal displacements and reversed metamorphism, generating the foreland basin of Bambuí Group. Later, the continental collisional tectonic evolved to the northern sector, with the collision between the Amazonian and the São Francisco cratons, controlled by NE lineaments and lateral transports (transpressional belt). The collision of the São Francisco and the Amazonian paleoplates took place much later, at around 570–540 Ma [87,88], leading to the development of the North Brasília Belt. The mega inflection of the Pirineus [20] and the overlapping zone may be the result of the interference between two distinct Neoproterozoic belts.

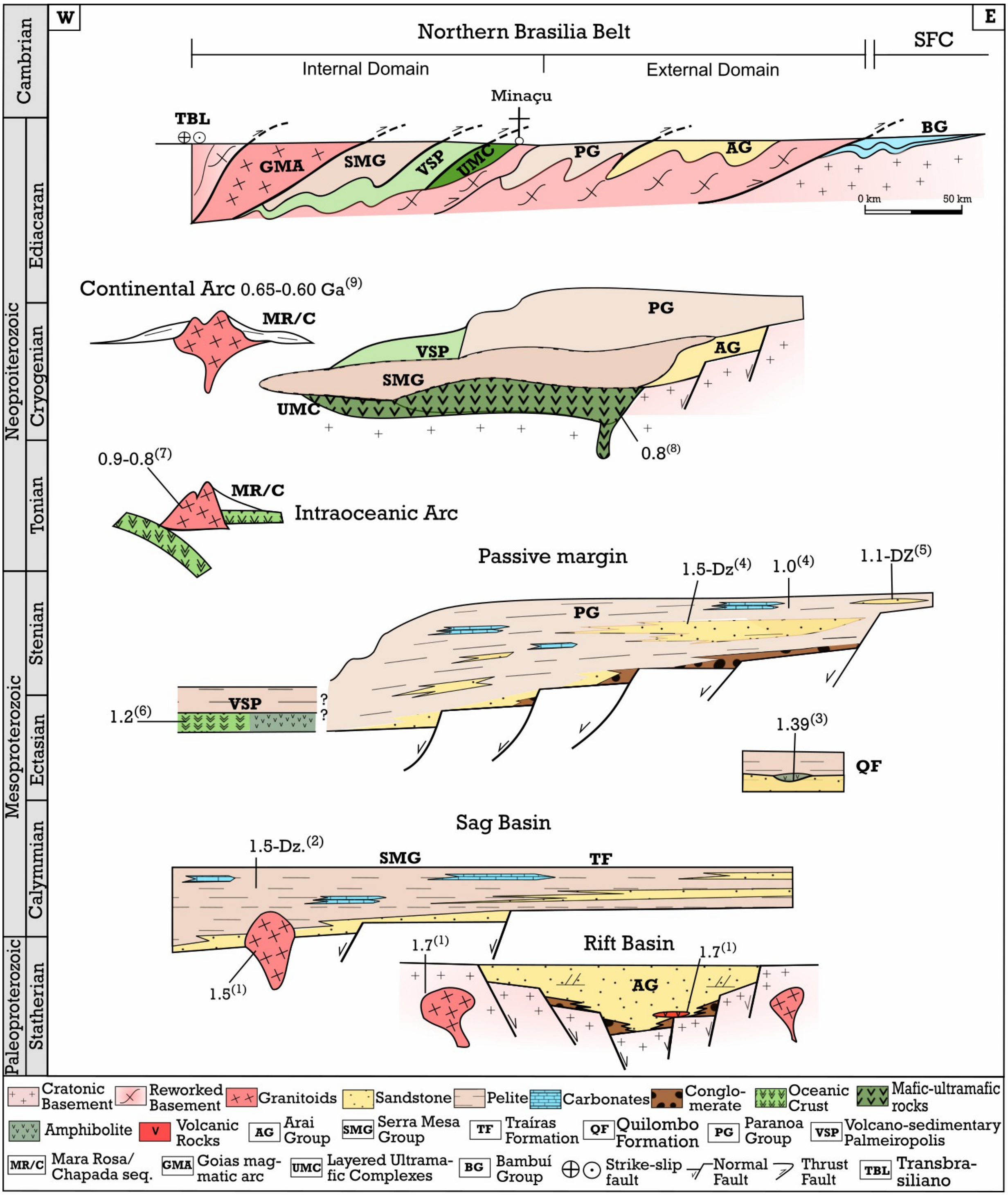

Figure 3. The Northern Brasília belt: sedimentary basins, extensional and contractional events, and geological evolution [14,16,47,49,63]. Geochronological data: 1—[65,68]; 2—[66,67] 3—[74]; 4—[71]; 5—[73]; 6—[47,75,77]; 7—[47,83]; 8—[47,76,77,79,80,82]; 9—[47,49,83]. Dz: Detrital zircon.

4. The Rio Preto Fold Belt

The Rio Preto belt occurs on the northwest limit of the SF Craton and is located in the northwest of Bahia and south of Piauí [1,89–93]. The Rio Preto belt is formed by the basement (archean–Paleoproterozoic migmatites and granitoids), Formosa Formation (mica schists, quartzites, greenschists. and amphibolites) of Paleoproterozoic age (~1.9 Ga) and by the Canabravinha Formation (metadiamictites, quartzites, and mica schist) of

Neoproterozoic age (850–600 Ma). The basement occurs locally to the southeast, close to the city of Barreiras-BA, and to the north, where it receives the name of Cristalândia do Piauí Complex (Figure 4). The Rio Preto belt represents an inverted Neoproterozoic intracontinental rift basin (showing hemi-graben geometry) with the double-thrust wedge produced by the oblique convergence between the São Francisco craton and the Cristalândia do Piauí block or microcontinent [89,92,93].

The Formosa Formation crops out in the northern portion of the belt, extending for ca. 20 km toward the north, reaching the region of the boundary between the states of Bahia and Piauí. It is composed of garnet-muscovite schists with layers of micaceous quartzites, metarhythmites, iron-manganese metacherts, chlorite-actinolite-epidote schist (greenschist), and, locally, ortho-amphibolite intercalations. The latter is particularly well exposed at the Angico farm, to the west of Formosa do Rio Preto town, where a 200 m thick ortho-amphibolite layer is concordantly intercalated with metasedimentary rocks. These amphibolites were interpreted as tholeiitic gabbros metamorphosed under epidote-amphibolite facies conditions (around 500 °C and 2–5 kbar), and U-Pb analyses of magmatic zircon crystals yielded a precise age of 1958.3 $\pm$ 16 Ma [94]. Thus, the Formosa Formation represents a paleoproterozoic basement of the Rio Preto belt (see Figure 4).

The Canabravinha Formation occurs in the southern portion of the Rio Preto belt, extending from the village of Cariparé toward the north for almost 40 km. It also occurs in the direction of the northern Paramirim Corridor, with an extension of 200 km to the northeast. It is composed of immature quartzites and metawackes, metapelites (locally carbonaceous), metarhythmites, metadiamictites with pebbles and cobbles, and, locally, metamarl. The quartzites and metawackes show lithic, feldspathic, carbonate-rich, and micaceous varieties. Conglomeratic quartzites show plane-parallel structures and graded bedding, suggesting sedimentation by turbidite currents. The vertical and lateral facies changes observed in the Canabravinha Formation characterize a transition from coarse-grained rocks on the south (metadiamictite and metawackes) to medium- and fine-grained facies on the north (metarhythmites and phyllites). The deposition of the Canabravinha Formation was interpreted as occurring in a submarine gravel-rich slope–apron environment with gravitational sedimentation [95]. The spectrum of U-Pb ages of the detrital zircons of the Canabravinha Formation differs from the Formosa Formation, spreading from 3000 to 900 Ma [95]. The Nd isotopes also indicate a larger variety of sources, with TDM model ages between 1.5 and 2.7 Ga. The Canabravinha Formation was deposited into Neoproterozoic asymmetrical rift basin (hemi-graben basin) with gravitational flows and turbiditic sediments (Figure 4). The diamictites of the Canabravinha Formation are interpreted as mass-flow deposits associated with a faulted margin of a rift basin [44,92] but might represent a reworking of glacial debris and, thus, probably a distal correlative of the Jequitaí and Bebedouro Formations [96], and of the Palestina diamictites of the Sergipano belt [44].

The Bambuí Group that outcrops on the São Francisco craton near the Rio Preto fold belt margin, was subdivided in western Bahia state into three formations [89,96], from the base to top (Figure 4): the São Desidério (dark gray limestones with intercalations of siltstones, correlated with Lagoa Jacaré Formation); Serra da Mamona (metasiltstones and slates, correlated with Serra da Saudade Formation); and Riachão das Neves Formation (meta-arkoses, metasiltstonesand metagraywackes correlated with Três Marias Formation).

Recently, ref. [97] studied the Cristalândia do Piauí Complex as part of the basement to the Rio Preto fold belt. The authors recognized ca. 3.2 Ga orthogneisses reworked at ca. 2.81 and 2.68 Ga, high-K syenogranites at 2.65 Ga and ca. 2.2 Ga metagranitoids with compositions varying from granodioritic with sanukitoid-type signatures to monzogranitic, and alkali-feldspar granitic with crustal signatures; garnet–biotite paragneiss with a maximum depositional age of ca. 1.95 Ga and intrusive mafic dikes at 2.07 Ga. The authors interpreted the Cristalândia do Piauí Complex or Block as part of the reworked NW margin of the São Francisco craton [97].

The overall architecture of the intracontinental Rio Preto belt is characterized by a double-thrust wedge, in which the southern and wider portion displays a clear vergence toward the São Francisco craton, whilst the northern and narrower branch verges north, as exemplified by the low angle thrust bringing the Formosa Formation over the Cristalândia do Piauí gneisses [89,98]. Neoproterozoic deformation, probably between 550 and 530 Ma, originated a complex, asymmetrical, and double-verging thrust wedge, whose southern branch propagated for over 100 km into the craton interior in the form of a thin-skinned deformation front. In the Rio Preto belt, three main deformation phases can be recognized [89,92,98]: phase D1 and D2 generated an S1 and S2 foliation (a penetrative crenulation clivage), and phase D3, with open folds and a spaced crenulation cleavage (S3). Phase D2 (the main deformational phase) is responsible for the development of the double-verging large-scale structure of the Rio Preto belt and conspicuous S2 foliation. The asymmetrical folds affecting the Bambuí Group in the external zone (São Francisco craton) grade progressively into tight to isoclinal folds in the internal portions of the Rio Preto fold belt, with S1, S2, and S3 foliations [89].

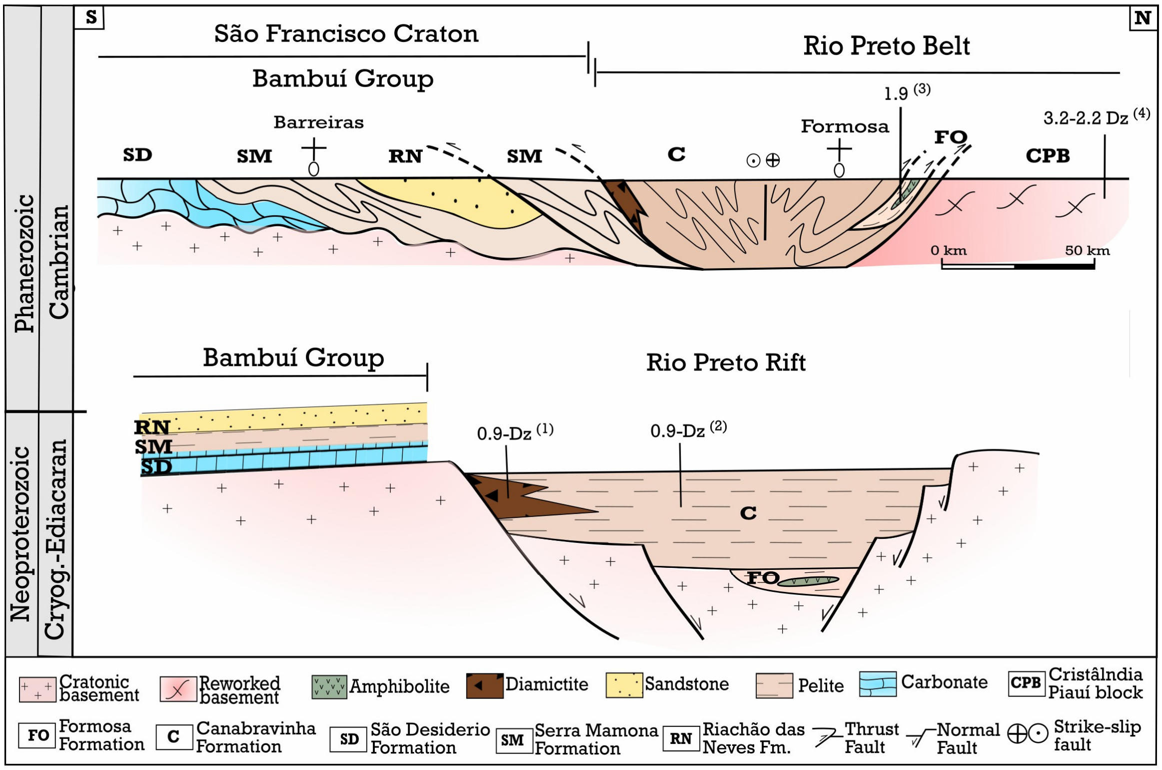

Figure 4. The Rio Preto Belt: sedimentary basin, extensional and contractional events, and geological evolution [89,92,93]. Geochronological data: 1—[95]; 2—[99]; 3—[94]; 4—[97]. Dz: Detrital zircon.

It was proposed that the double-thrust wedge was produced by the oblique convergence between the São Francisco craton on the south and the Cristalândia do Piauí block on the north [93,98]. This convergence generated frontal thrusts followed by back thrusts. The continuation of the process led to an overall right-lateral transpressional modification of the system, thereby generating the prominent Malhadinha–Rio Preto shear zone in the central portion of the belt.

The stratigraphic and structural relations between the Rio Preto and Santo Onofre Groups in the Rio Preto belt (border of the SF craton) and the north of the Paramirim Corridor (BA) were presented by [99]. The Rio Preto Group, involved in the fold–thrust belt along the northwestern cratonic boundary, comprises a garnet–quartz–mica schist, quartzite, chlorite–sericite schist, ferriferous quartz schist, micaceous quartzite, metarhytmite, phylite, and metaturbidite. The Santo Onofre Group occurs exclusively in the Paramirim corridor and is composed of quartzite and minor carbonaceous or Mn-rich phylite. These units record sedimentation in shallow to deep-water marine settings related to two distinct rift basins and were deformed and metamorphosed under greenschist facies conditions during the Brasiliano orogeny. New detrital zircon geocronology U-Pb ages constrain the maximum depositional ages of ca. 971 Ma for the Santo Onofre Group and ca. 912 Ma for the Rio Preto Group [99]. The study area shows the interference of two distinct generations of tectonic structures associated with the West Gondwana amalgamation. The N-S striking structures of the Paramirim corridor probably represent the propagation of the Araçuaí orogenic front toward the interior of the São Francisco craton, and the WSW-ESE trending of Rio Preto Belt represents the transpressive inversion of a preexistent rift structure along the NW craton margin.

5. The Riacho Do Pontal Orogen

At the northern limit of the São Francisco craton, the Riacho do Pontal belt occurs between the states of Bahia, Pernambuco, and Piauí [1,100,101]. It is a hot and dry region of northeastern Brazil.

Many different data suggest the division of the Riacho do Pontal Orogen into three tectonostratigraphic zones: external, central, and internal [92,100–103]. To the north, it is bounded by the E-W trending dextral strike-slip western branch of the Pernambuco shear zone. The basement is represented by TTG-orthogneisses from the Gavião/Sobradinho block of the São Francisco craton [92] and crops out in the Sobradinho dam area. Tectonic scales of basement rocks (banded migmatitic gneisses) occur locally within the fold belt.

In its internal zone, the Riacho do Pontal Belt comprises highly reworked Archean /Paleoproterozoic migmatitic basement slices and volcano–sedimentary sequences such as the Paulistana, Santa Filomena, and Morro Branco complexes. These are also intruded by large quantities of igneous rocks, which include both the Brejo Seco and Sao Francisco de Assis mafic–ultramafic complexes [92,103,104] and the Afeição Suite augen-gneiss [105,106]. The units have undergone amphibolite facies metamorphism and intense deformation due to thrust and strike-slip shear zones. The central zone of the Riacho do Pontal belt shows a complex synformal structure trending EW and featuring ophiolitic rocks from the Monte Orebe Complex. The Riacho do Pontal belt's southernmost outer zone exhibits a south-trending nappe system consisting of Casa Nova Group supracrustal rocks metamorphosed under greenschist facies (Barra Bonita and Mandacaru Formations).

A comprehensive examination of the plutonic rocks found in the Afeição Suite was conducted, indicating their association with the Tonian Cariris Velhos magmatic arc of the Borborema Province [106]. The Afeição Suite is primarily composed of high-silica ferroan and magnesian granites–granodiorites that are calc-alkaline, high-K, and peraluminous. Additionally, the chondrite normalized REE patterns are moderately to highly fractionated with a negative Eu anomaly. Incompatible elements exhibit a negative Nb-Ta anomaly, which is reminiscent of convergence setting granites. Zircon U-Pb data providing a crystallization age between 1000 and 960 Ma confirm a correlation with the Cariris Velhos belt [106]. Support for this correlation is provided by εNd(t) values between -1.0 and $+3.1$ and TDM model ages of 1.2–1.5 Ga [106–108]. The Afeição suite rocks are remnants of the roots of Tonian magmatic arcs, which were intruded into the basement of the Riacho do Pontal orogen.

The Paulistana Complex consists of garnet-mica schists and muscovite quartzites, with intercalations of greenschists (metabasalts), amphibolites (metagabbros), and ultramafic lenses [103]. The Paulistana Complex metasedimentary rocks are oriented NE-SW and dip northwesternward at angles ranging from 20° to 60°. These lithotypes often intercalate with metagabbros, garnet–amphibolites, metapyroxenites, tremolite–actinolite schists, and metacherts [92]. Zircon crystals extracted from a metagabbro indicate a Concordia age of 882.8 ± 4 Ma [101]. Additionally, based on detrital zircon data, the maximum depositional is calculated at 900 Ma [109,110]. The Paulistana Complex may be interpreted as a constituent of a continental rift setting [101], as shown in Figure 5. The Morro Branco Complex is the dominant feature of the western internal zone. It is a metavolcanosedimentary sequence, primarily composed of metarhythmite with intercalations of metabasalt, metarhyolite, and mafic to intermediate metatuff. Additionally, the Morro Branco Complex is intruded by the Brejo Seco Complex, a ca. 900 Ma (Sm-Nd whole-rock isochron [104]) mafic–ultramafic intrusion with Ni-Cu-PGE deposits.

The Brejo Seco Complex is a tectonically interleaved intrusion within the Morro Branco volcanosedimentary sequence, approximately 10 km in length. The complex stratigraphy can be classified into four major zones [104]: Lower Mafic Zone (LMZ), Ultramafic Zone (UZ), Mafic Transitional Zone (MTZ), and Upper Mafic Zone (UMZ). The Brejo Seco complex consists of a thin basal mafic unit (metagabbros and troctolites), succeeded by serpentinized dunite, layered troctolite–gabbro, leucogabbro, minor anorthosite, ilmenite gabbro and ilmenite–magnetitite [92,104]. The entire complex, with a maximum thickness of 3 km, is characterized by tectonic inversion. The ultramafic units are located in the northern portion of the region and overlay the mafic units to the south. The northern and southern contacts are marked by EW-trending reverse shear zones. The Brejo Seco Complex is a typical layered intrusion of mafic–ultramafic rocks that was formed approximately 900–850 million years ago in a continental rift environment [101,104]. The Tonian Brejo Seco rift shares similarities with the Cryogenian Canindé rift located in the adjacent Sergipano fold belt (see below). The Brejo Seco Complex is interpreted as intruded in a continental extension setting, probably related to the emplacement of a mantle plume [104] (see Figure 5). The Tonian rift, with a roughly E-W orientation, can be identified in the inner section of the Riacho do Pontal belt. It comprises the Brejo Seco Complex (a layered mafic–ultramafic intrusion) and the Paulistana Complex (a volcano–sedimentary sequence). This rift was subsequently deformed and metamorphosed during the Brasiliano Cycle.

The Santa Filomena Complex is located in the northeastern region, situated between the Pernambuco lineament in the north and the Monte Orebe Complex in the south. The complex consists of quartzites, muscovite, biotite, garnet, kyanite, staurolite, cordierite, and sillimanite schists, with occasional local calcitic marble and minor metamafic intercalations. It outcrops in the internal portion, toward the north of the orogen and exhibits metamorphism in the amphibolite facies and intense deformation. Peak metamorphic conditions are estimated to be around 640 °C and 12 kbar [110]. The predominance of ages around 800–750 Ma from detrital zircon populations of the Santa Filomena Complex [109,110] suggests that it has a Tonian–Cryogenian age. The Santa Filomena Complex was probably a passive margin over the Pernambuco-Alagoas massif (PEAL) and can be correlated with the Barra Bonita Formation. Thus, extensional efforts continued to dominate the region during the late Tonian and early Cryogenian, resulting in the evolution of a rift into a passive continental margin located to the north of the São Francisco paleocontinent (Figure 5).

The Riacho do Pontal belt's central zone exhibits a 100 km long, east–west trending synformal structure recognized as the Monte Orebe synform [103,111]. The geology of the area is complex, with both south-verging thrusts and E-W strike-slip shear zone systems. The central zone is dominated by the Monte Orebe Complex, consisting of basic metavolcanics (actinolite schists, ortho-amphibolites, and metatuffs) interlayered with deep-sea pelagic metasedimentary rocks, particularly metachert (sometimes iron-rich) and garnet–mica schist, as well as local occurrences of metagreywacke and quartz-schist [92,103]. There is a predominance of hornblende–amphibolites, metabasalts with preserved primary texture indicating submarine eruptions, actinolite–tremolite schists, metachert layers, quartzites, phyllites, graphite schists, and tuffs. The Monte Orebe Complex protoliths have a tholeiitic, MORB-type affinity [112,113]. Sm-Nd isotopic data yield a whole rock isochron age of 819 $\pm$ 120 Ma with an initial εNd(t) = +4.4, suggesting a depleted mantle source [113]. The Monte Orebe Complex is interpreted as being composed of remnants of a Neoproterozoic ophiolite sequence of about 820 Ma, which marks the development of new oceanic crust and separates the Borborema province (PEAL block) from the São Francisco paleocontinent to the south [113]. The data presented suggest that the metabasalts of the Monte Orebe Complex represent preserved oceanic crust that formed between the São Francisco and

Pernambuco-Alagoas blocks during the Tonian–Cryogenian and was subsequently obducted during the early stages of the Brasiliano orogeny [93,101,113]. The lower plate (São Francisco paleocontinent) is represented by lower Bouguer anomaly values to the south, while the upper one (western edge of the Pernambuco-Alagoas domain) is represented by higher Bouguer values to the north [93,101,113–115].

The southernmost outer zone of the Riacho do Pontal belt is characterized by a south-trending nappe system composed of supracrustal rocks that overlie the basement of the São Francisco craton in the Sobradinho dam area. The outer zone includes the Casa Nova Group, which is divided into two units: the Barra Bonita Formation and the Mandacaru Formation. The Barra Bonita Formation consists of metapelitic rocks and muscovite quartzite with marble lenses and is interpreted to have been deposited in a shallow marine platform environment [92,101,116]. The marble lenses can reach thicknesses of up to 200 m and locally preserve original sedimentary structures. This formation represents a passive margin, with detrital zircon ages ranging from 1.6 to 2.1 Ga and TDM values between 2.4 and 1.5 Ga. Thus, the Barra Bonita Formation (to the south on the São Francisco paleocontinent) and the Santa Filomena Complex (to the north on the PEAL) form the Tonian–Cryogenian passive margin basin of the Riacho do Pontal belt (Figure 5). Carbon and strontium isotope data for marble intercalations within the Barra Bonita Formation are also very similar to those of the Salitre Formation of the Una Group and the Olhos D'água Formation (Sergipano fold belt), suggesting a broad Neoproterozoic carbonate platform in this area [93,101]. It is therefore possible to infer Neoproterozoic sedimentation with shallow-water carbonates on the São Francisco paleocontinent (Salitre Formation), transitioning northward to pelites and carbonate lenses on the continental margin (Barra Bonita Formation).

The Mandacaru Formation consists mainly of mica schists with small garnets and thin layers of metagraywacke. Some exposures show a rhythmic structure with centimetric sandstone beds alternating with decimetric metapelite beds. The composition and geochemical data support a deep-sea turbiditic, syn-orogenic sedimentation record for the Mandacaru Formation [116]. Furthermore, the Mandacaru Formation shows distinctive provenance patterns, with TDM model ages averaging 1.6–1.4 Ga [92,101,109,117]. U-Pb detrital zircon data from the study show a peak at 1.0 Ga, with the youngest detrital zircon around 640–665 Ma [92,101,109]. These results suggest that the internal zone of the belt (a probable continental magmatic arc) was the source of the Mandacaru Formation. Thus, there is an important variation in sedimentary provenance in the Riacho do Pontal belt: the Barra Bonita Formation represents a passive margin with southern provenance, i.e., from the São Francisco palaeocontinent, while the Mandacaru Formation represents a retro-arc foreland basin with northern provenance.

The convergence phase in the Riacho do Pontal started at ca. 630–620 Ma, with the emplacement of the calc-alkaline Betânia granite, probably related to a continental magmatic arc setting [118]. It culminates in an inversion of the passive margin basin, obduction of oceanic crust slices, and sedimentation of the Mandacaru Formation syn-orogenic rhythmites (greywackes-pelites) in the retroarc basin [93,101]. The Riacho do Pontal belt contains a large number of Neoproterozoic granitoid plutons emplaced from the syn- to the post-collisional development stages. The syn-collisional magmatism of the Rajada Suite is represented by tabular bodies of mesocratic, fine- to medium-grained, two-mica orthogneisses of 630–620 Ma. The Serra da Esperança Suite represents syn- to late-collisional magmatism [92,93,101,103,109].

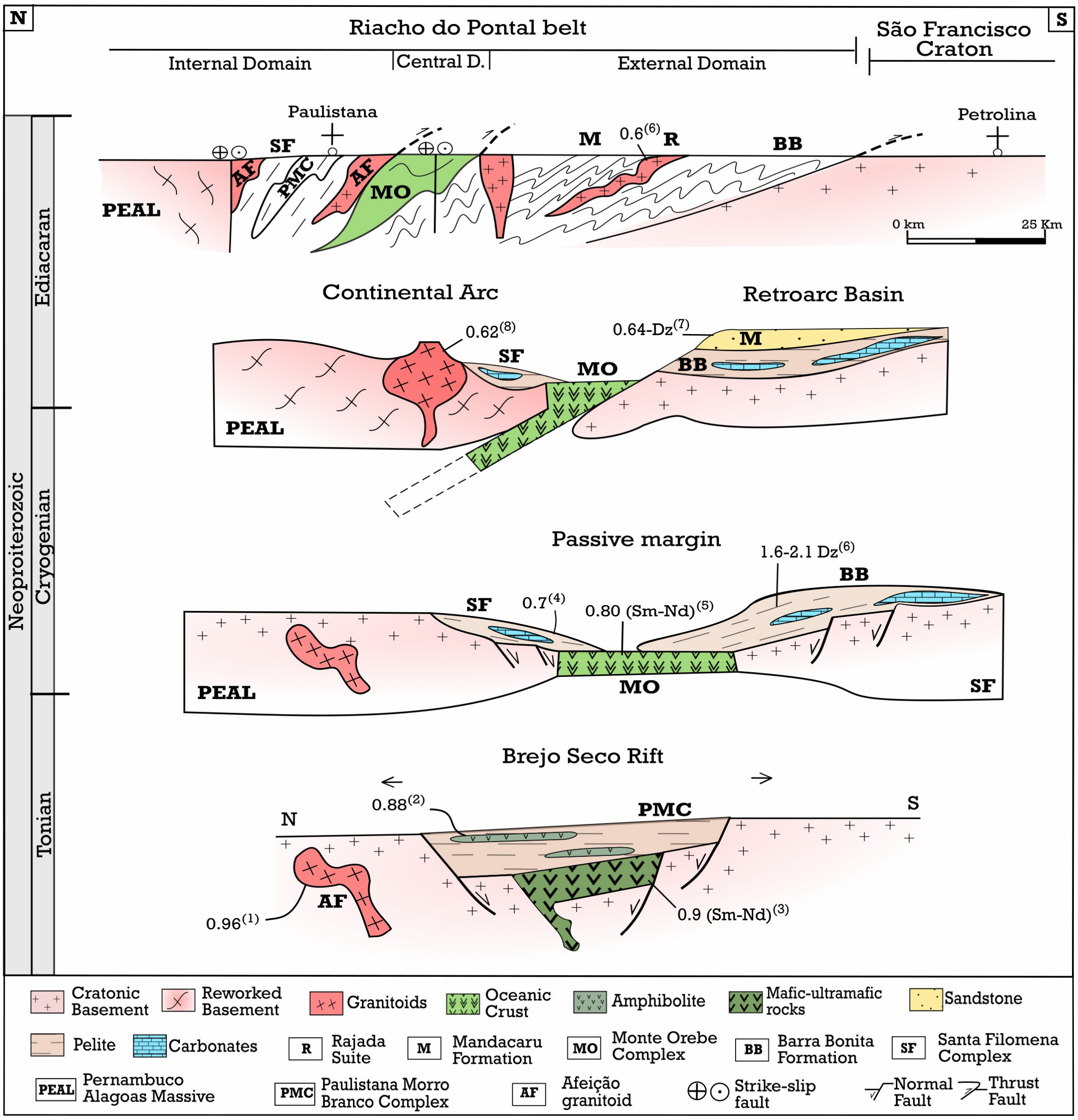

Figure 5. The Riacho do Pontal Belt: sedimentary basins, extensional and contractional events, and geological evolution [92,93,101,109]. Geochronological data: 1—[106]; 2—[101]; 3—[104]; 4—[109,110]; 5—[112]; 6—[101]; 7—[101,109]; 8—[118]. Dz: Detrital zircon.

The orogenic deformation of the Brasiliano Cycle occurred in the Riacho do Pontal belt in two tectonic phases: D1 represents early tangential deformation with thrusts and nappes verging southward toward the São Francisco craton; D2 represents late, high-temperature dextral strike-slip deformation, characteristic of the internal portion (Pernambuco lineament) [92,101,103]. The D1 deformation was of the progressive tangential type, generating two foliations S1-S2, as well as thrusts and nappes verging to the south, with inverted metamorphism, higher toward the top (upper units) and associated with Rajada Suite (620 Ma) syn-collisional intrusions. A down-dip stretching lineation, plunging between NW and NNW, is normally associated with the S2 foliation. The tangential deformation D1 evolved from a thick-skinned domain on the central north to a thin-skinned zone on the south, with detachment surfaces and klippes over the basement of the São Francisco craton. The second phase (D2) is dextral strike-slip motions accommodated along EW-trending shear zones, important in the central and internal domains. The West Pernambuco shear zone (or Pernambuco lineament) is the main structure related to the D2 phase. This continental-scale shear zone is associated with a high-grade mylonitic foliation that overprints all units of the internal zone of the belt [92]. Proterozoic units located in the northern region of the Sao Francisco craton are strongly affected by the intense deformation of the Riacho do Pontal orogen [119].

6. The Sergipano Orogen

The Sergipano belt is a Brasiliano/Pan-African fold-and-thrust belt located on the northeastern edge of the São Francisco craton in the states of Bahia, Sergipe, and Alagoas [1,100,120–124]. It was formed by a continental collision between the São Francisco-Congo Paleocontinent and the Pernambuco Alagoas Massif (PEAL) during the Brasiliano/Pan-African orogeny [100,120–127]. The basement of the São Francisco craton, to the south of the Sergipano belt, is a granite–greenstone belt sequence with archean–paleoproterozoic high-grade terranes. The Pernambuco-Alagoas massif (PEAL), to the north of Sergipano belt, comprises Archean–Palaeoproterozoic high-grade gneisses and migmatites, early Neoproterozoic rocks (Cariris Velhos), and Neoproterozoic volcano–sedimentary supracrustal belts intruded by Neoproterozoic granitoids [100,128,129].

The Sergipano belt is divided from north to south into the Canindé, Poço Redondo, Marancó, Macururé, Vaza Barris, and Estância tectonostratigraphic domains, limited by important contractional shear zones [120,122,124,125,130]. The northern Canindé, Poço Redondo, Marancó, and Macururé domains show amphibolite metamorphic facies. Toward the south, the Vaza Barris domain has greenschist facies, and the cratonic Estância domain presents unmetamorphosed rocks.

Some researchers performed stratigraphic studies on the Vaza Barris domain and divided the supracrustal sequences into two groups, the Miaba and Vaza Barris groups [131], later modified by [121,132]. The Macururé domain consists mainly of garnet micaschist, phyllite, and metarythmithe, with some quartzite and marble [130]. These metasedimentary rocks were intruded by granitic plutons dated at about 625–630 Ma [133,134]. The Marancó domain is mainly formed by a metavolcanosedimentary sequence with 603 Ma, with dacites-andesites and granodiorite stocks dated at 595 ± 11 Ma [135,136], suggesting an Ediacaran continental arc. The Poço Redondo domain is composed of biotite gneisses–migmatites (960–980 Ma U-Pb SHRIMP ages [135]), granitic intrusions, such as the Serra Negra augen-gneisses (952 Ma U-Pb SHRIMP ages [124,125,135]), and granodiorite and leucogranite sheets. The Canindé domain comprises a metavolcano–sedimentary sequence (Novo Gosto and Gentileza units) and the Canindé gabbro–leucogabbro complex (gabbro, gabbronorite, peridotite, and pegmatitic gabbro) and granodioritic–granitic plutons. The Canindé domain age ranges from 740 to 609 Ma [124–126,137,138].

Tonian–Cryogenian extensional tectonics (800–640 Ma) occurred on the stretched, rifted margin of Archean–Paleoproterozoic basement, giving rise to (1) the 0.95 Ga Serra Negra A-type crustal melt granites; (2) the Canindé rift (715–640 Ma) formed between the Pernambuco-Alagoas block (PEAL) and the Poço Redondo/Marancó domain; and (3) the Miaba rift in the south on the stretched São Francisco paleocontinent (see Figure 6).

The Cryogenian Canindé rift shows a bimodal association of A-type granites (715 Ma) and volcano–sedimentary Novo Gosto-Mulungu-Gentileza units [132,137] made up of fine-grained amphibolites intercalated with metapelites, metacherts, graphite schists, calc-silicate rocks and marbles, crosscut by mafic and felsic dykes, an elongated pink granite sheet (Garrote unit) and gabbros. LA-ICP-MS U–Pb zircon dating of one amphibolite sample from the Novo Gosto unit resulted in an age of 743 ± 3 Ma [126]. The Canindé gabbroic complex (NW-trending, 40 km long, 3–5 km wide) comprises three main rock groups: (1) leucogabbros and troctolites; (2) Fe-Ti oxide gabbros; and (3) mafic–ultramafic cumulates: norites, pyroxenites, and hornblendites. Diorites (688 Ma) and rapakivi granites (684 and 641 Ma) also occur. The Canindé gabbroic complex is interpreted as a continental-type layered intrusion in an extensional intracontinental rift basin [124,125,137,139]. The mafic–ultramafic Canindé intrusion is a single stratiform-type intrusion emplaced around 703.5 ± 1.6 Ma (LA-ICP-MS U–Pb zircon age [138]).

The Miaba rift consists of the Itabaiana Formation (quartzites), the Ribeirópolis or Jacarecica Formation (phyllites), and the Jacoca Formation (metacarbonates), with 200–1000 m thick [120,121,140,141]. The Itabaiana Formation rests unconformably on basement gneisses and migmatites of the Itabaiana and Simão Dias domes in the southern belt. The unit comprises a basal level of poorly sorted feldspathic metasandstones with cross-bedding stratification and metaconglomerates deposited in alluvial and fluvial environments that pass gradually up section into well-sorted sandstones deposited in the shallow marine environment. It is overlain by phyllite and metadiamictite with pebbles of gneiss and quartzite and intercalations of metagreywacke and metavolcanics (Ribeirópolis Fm., 300 m thick). Above, the Jacoca Formation is 0–150 m thick and has intercalated metadolomite, metalimestone, and phyllite. U-Pb detrital zircon geochronologic investigations indicate the following ages for the youngest zircon populations within the Miaba rift: 2000 Ma (quartzite from Itabaiana Formation) and 780 Ma (metagreywacke from Ribeirópolis Formation), suggesting a Cryogenian extension tectonics for the Miaba rift [124,125,142].

Stratigraphically, the Vaza-Barris Group is divided into Capitão Palestina Formation (metadiamictite, metasiltite, metagreywacke, 100–2000 m thick) succeeded by grey to black limestone and dolomite, occasionally with phyllite intercalations (Olhos D'Água Formation, 200–1000 m thick) and phyllite, metagreywacke of Frei Paulo Formation, with 1000–1500 m thick [120,131,132,141,143]. The metadiamictites of the Capitão Palestina formation are interpreted as subaqueous debris flows adjacent to normal faults and glacially influenced deposits [44,141,143] and have clasts lithotypes composed of granite-gneiss, sandstone, carbonate, and schist. The lateral variation in lithofacies and thicknesses is interpreted as sedimentary infilling under a syn-depositional extensional regime with sedimentation tectonically controlled by the basement domes (horst) and normal faults [140]. The youngest detrital zircon grains from the Capitão Palestina Formation are 653 Ma, and from the Frei Paulo are 620 Ma [123,124,142]. From carbon and oxygen isotopes of the Olhos d'Água and Jacoca formations and the diamictites and conglomerates below them, both Sturtian (720–660 Ma) and Marinoan (650–635 Ma) glacial epochs can be recognized in the Sergipano belt [143]. The geochronological data suggest that the deposition of the Jacoca Formation carbonates is younger than 780 Ma in the Miaba rift and that the deposition of the Olhos D'Agua Formation probably took place between 650 and 620 Ma into the rift to passive margin basin [44,124,125,141,143]. Strontium isotope ratios within the range of late Neoproterozoic seawater (0.7060–0.7090) provide additional support and, along with detrital zircon age data, suggest that the Jacoca Formation (and correlative Acauã Formation) is probably mid-Cryogenian (Sturtian), while the Palestina and Olhos D'Água formations represent the diamictite-cap carbonate pair of the late Cryogenian (Marinoan) glaciation [44,143].

The Macururé domain shows metarythmithe, sometimes with graded beds, interpreted as metaturbidites, feldspathic-aluminous mica schists with minor intercalations of quartzite, marble, and metavolcanic rocks, lenses up to 200 m in length of amphibolite, garnet amphibolite, and chlorite schist [124,130]. Together with the Vaza Barris Group, it probably comprises a submarine fan depositional environment in a passive margin setting, with sedimentation by gravitational flows. There is a predominance of cohesive and noncohesive debris flow to the south (diamictites of the Vaza Barris Group) and a predominance of dilute turbidity currents to the north (turbidites of the Macururé Group [130,141]). Detrital zircon ages of quartzite and mica schist in the Macururé domain indicate dominantly Paleoproterozoic, Mesoproterozoic, and early Neoproterozoic, suggesting that the basement was the main provenance of the Macururé sediments. No zircons younger than 856 Ma were found [124,142,144]. The sedimentation age of the Macururé Group ranges from ca. 850 Ma (younger detrital zircon grains) to the age of the intrusive granites–granodiorites—630 Ma [124,132,134]. The Vaza Barris and Macururé domains are interpreted as a rift to the passive margin basin of the Sergipano belt, although some occurrences, such as the Graccho Cardoso meta-conglomerate [124], suggest the involvement of a retroarc basin (see Figure 6).

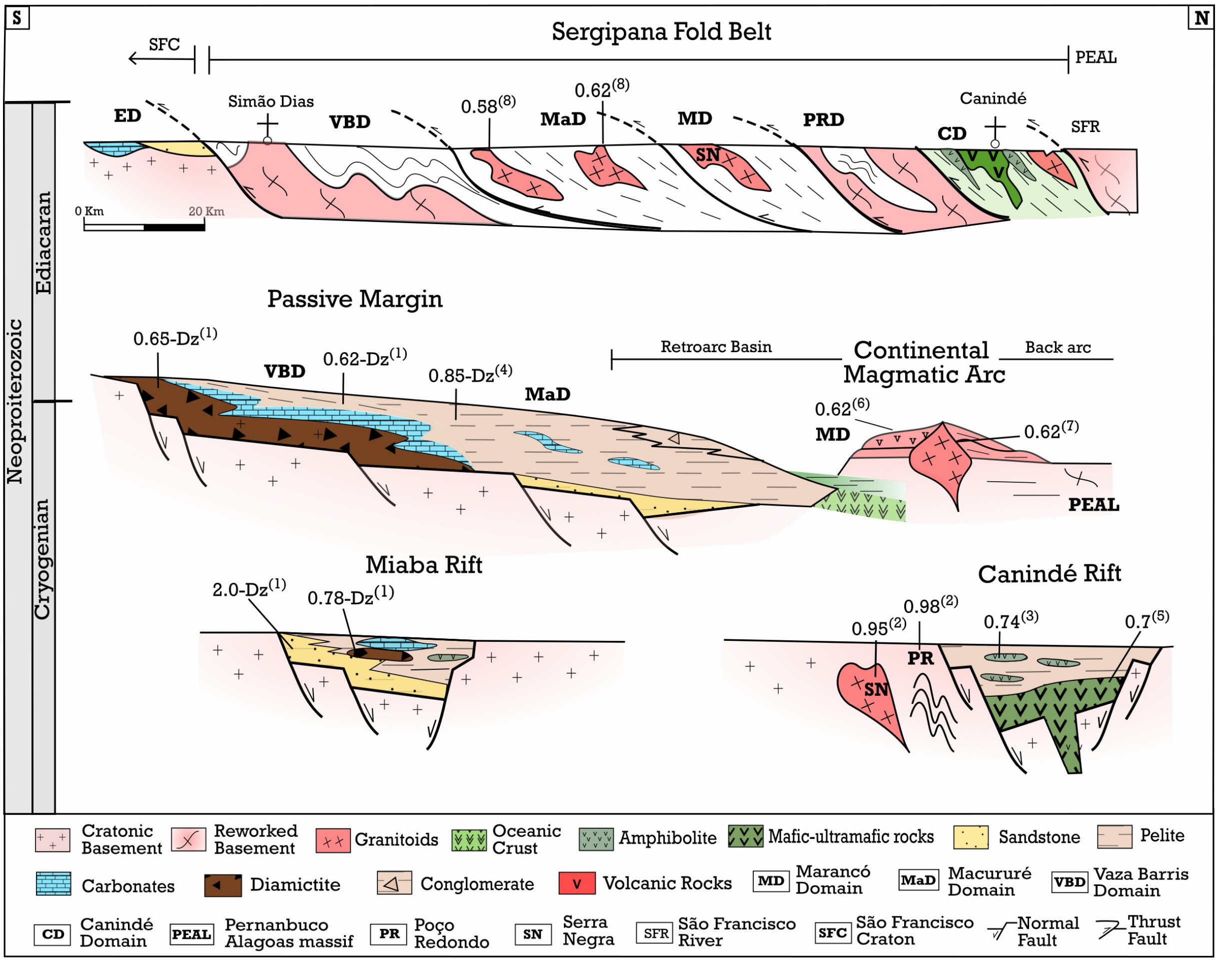

Figure 6. The Sergipano Belt: sedimentary basins, extensional and contractional events, and geological evolution [124,125,142]. Geochronological data: 1—[124,142]; 2—[124,135]; 3—[126]; 4—[142]; 5—[124,137,138]; 6—[124,134,135]; 7—[145]; 8—[133,134]. Dz: Detrital zircon.

The Marancó domain shows a volcano–sedimentary sequence tectonically imbricated with Serra Negra anorogenic granitoid. The volcano–sedimentary sequence comprises greenschist to amphibolite facies rhythmites, pelites, psammitic metasedimentary rocks, and metapiroclastic (tuff) interleaved with volcanic calc-alkaline metandesite to metadacite lenses, metagabbro, and serpentinites-peridotites. Geochronological data from the Marancó volcanic rocks (dacite) indicate ages of 602 ± 4 Ma, and whole-rock geochemistry suggest that the calc-alkaline metavolcanic rocks most likely belong to a continental magmatic arc [124,134,135]. Silva Filho [136] recognized serpentinized peridotites and metagabbros in the south of the domain and interpreted them as ophiolite fragments. Thus, the Marancó domain shows fragments of oceanic crust and rocks of magmatic arc origin.

The metavolcanosedimentary Araticum Complex (sillimanite-garnet schists, marbles, amphibolites) within the northeastern part of the Sergipano Belt, near the Jirau Ponciano Dome, shows detrital zircon with populations of Cryogenian-Ediacaran (ca. 660–620 Ma) suggesting back-arc sedimentation, with source areas from continental magmatic arcs [145]. The Poço Redondo domain has a sigmoidal shape in geological maps and represents the basement of the Pernambuco Alagoas massif (PEAL) tectonically imbricated into the Sergipano Belt (Figure 6). It shows a migmatitic gneiss complex with intrusions of granodioritic-tonalitic rocks with zircon U-Pb SHRIMP ages of 980 ± 4 Ma and 961 ± 38 Ma [124,135].

The stratigraphic units within the Sergipano Belt were involved in significant tangential deformation toward the craton (D_1 event) approximately 620–570 Ma ago. The D_1 event is the most penetrative in the Sergipano Belt and was associated with the main phase of collision between the São Francisco craton and the Pernambuco-Alagoas Block. It gave rise to pervasive south-verging thrusts and nappes throughout most of the metasedimentary domains in the belt. To the south, the cratonic domain shows subhorizontal sedimentary covers, and to the north, the Vaza-Barris domain shows polydeformed rocks with steep S_1–S_2 schistosity and inverse ductile–brittle shear zones [124,141]. The Macururé domain shows subhorizontal S_2 foliation and refolding [141]. The internal domains show steep S_2 foliation with oblique shear zones. Convergence of the Pernambuco-Alagoas block and the São Francisco craton led to the deformation of the passive margins and emplacement of granite bodies, mainly in the internal domain of the belt. Two granite age groups were recognized: 630–618 Ma in the Canindé, Poço Redondo, and Macururé domains, related to a volcanic arc, and 590–570 Ma granites (S-type) in the Macururé metasedimentary domain, related to continent–continent collision [134].

7. The Araçuaí Orogen

The Araçuaí Belt occurs at the curved southeastern margin of the São Francisco craton, showing a transition to the south with the Ribeira belt. The Araçuaí Belt consists of basement (units older than 1.8 Ga and rift–sag basin of the Espinhaço Supergroup), a Tonian rift, the Cryogenian rift–passive margin Macaúbas Group, as well as the syn-orogenic Salinas Formation and the high grade metamorphic–granitic core complex, the Jequitinhonha and Nova Venécia Complexes [146–151] (Figure 7).

The Paleo-Mesoproterozoic Espinhaço Supergroup is composed of ca. 5000 m-thick succession of quartz-rich sandstones, pelites, conglomerates, and volcanic rocks accumulated in an intracontinental basin (rift to rift–sag), with low-grade metamorphism [152–155]. The Neoproterozoic Macaúbas Group represents an extensive, and up to 10 km = thick sedimentary succession metamorphosed under greenschist to amphibolite facies, which crops out along most of the northern Araçuaí belt.

The oldest basin-forming episode recorded by the Macaúbas Group is represented by a Tonian rift between ca. 900 Ma and 850 Ma [151,156–158]. The onset of this event is marked by bimodal magmatism, which comprises (1) the Formiga-Pedro Lessa mafic dykes—930 to 895 Ma [159–161] and (2) the A-type granites of the Salto da Divisa Suite—ca. 875 Ma [162,163]. It occurs as intrusions into the basement and into the Espinhaço Supergroup.

The Tonian rift is about 250 km long in the NE-SW direction and 150 km wide, almost always covered by the middle–upper units of the Macaúbas Group. The Tonian rift is filled by continental to shallow marine sedimentary rocks of the Matão, Duas Barras, Domingas, Capelinha, and Rio Peixe Bravo formations [156,164–166]. U-Pb detrital zircon age determinations on these units indicate Archean to Neoproterozoic sources and a maximum depositional age compatible with the rift-related magmatism [157,158,165]. The Matão and Duas Barras Formations comprise 100–200 m thick, alluvial, and fluvial breccias, conglomerates, and sandstones with cross-bedding and paleocurrents toward NE and NW [156,164]. Detrital zircon ages set a maximum depositional age for the Duas Barras Formation at 900 $\pm$ 21 Ma [157]. To the top, there are pelites and stromatolitic carbonate lenses (Domingas Formation) deposited in shallow marine conditions during a transgressive episode [164]. The Capelinha Formation contains schists and quartzites (1500 m thick) and interbedded tholeiitic metabasalts, recording a syn-sedimentary magmatism dated at ca. 957 $\pm$ 14 Ma [165]. The geochemical data from orthoamphibolites suggest tholeiitic protolith related to a continental rift setting. In the region of Terra Branca and Planalto de Minas, greenschists (tholeiitic metabasalts) are dated at 890 Ma and interbedded with a marine volcano–sedimentary sequence (400 m thick) of the Tonian rift [166]. The metabasalts (greenschists) are an important magmatic activity related to expressive lithospheric thinning and mantellic influence during rifting [166].

After an erosive phase, extensional tectonics occurred and a renewed rifting event in the Cryogenian period led to the accumulation of gravitational sediments with glacial influence. The onset of the extension is marked by the intrusion of the anorogenic magmatic rocks of the South Bahia Alkaline Province exposed along the northern Araçuaí Orogen (730–675 Ma) [167].

The Serra do Catuni Formation from the Macaúbas Group comprises massive diamictite with local sandstone and pelite intercalations. Distinctive glacial sedimentary features include dropstones in metarythmithes, boulders, and striated flat-iron-shaped clasts [168]. The youngest detrital zircon grains constrain the maximum depositional age at 933 ± 8 Ma [157]. Although dubious, the Serra do Catuni Formation may be related to the Sturtian glaciation (ca. 720–660 Ma).

The Chapada Acauã Formation from the Macaúbas Group consists of massive and graded sandstones and pelites, composing a cyclic succession of sandy to muddy turbidites with local diamictite intercalations. Detrital zircon grains from a quartzite of the Upper Chapada Acauã Formation suggest a maximum depositional age of around 864 ± 30 Ma [147] and 743 ± 7 Ma [158].

In the Macaúbas Group, the Nova Aurora Formation represents the recurrence of diamictite sedimentation with debris flow, sandstones, and rare pelite intercalations. Thick layers of Rapitan-type iron-rich diamictite and banded iron formations occur locally [169,170]. The youngest detrital zircon grains found in these units show Tonian and local Cryogenian ages [158]. Castro [171,172] described in the Turmalina region a diamictite-bearing facies associations correlative to the Nova Aurora Formation, the upper diamictite bed of the Macaúbas Group. They suggest deposition by glaciomarine mass flows and turbidity currents within a submarine fan, followed by fine-grained turbiditic sedimentation along fan fringes partially influenced by iceberg discharges [171,172]. Detrital U-Pb ages indicate that the Nova Aurora Formation was deposited between the Late Tonian and Cryogenian—750–667 Ma [171]. The younger detrital zircon is 667 ± 11 Ma, suggesting a Marinoan glaciation for the Nova Aurora Formation in the Macaúbas passive margin. The younger detritic zircon also indicates that the Nova Aurora Formation and the Marinoan glaciation were partially contemporary with the oceanic crust from the Ribeirão da Folha Formation. The Ribeirão da Folha Formation crops out to the east, with pelite, sandstone, and ophiolitic remnants in the central Araçuaí Orogen [173,174]. Thrust slices of metamafic and meta-ultramafic rocks with ocean-floor lithochemical and isotopic signatures constitute tectonically dismembered ophiolite complexes in the Ribeirão da Folha Formation [146,147,175]. Zircon crystals from a plagiogranite sample yielded an LA-ICP-MS U-Pb age around 660 Ma [173], further re-analyzed via U-Pb SHRIMP at 645 ± 10 Ma [176]. This age, together with U-Pb zircon data from the youngest ophiolite slivers found in the Araçuaí orogen—ca. 600 Ma [174] suggest oceanic spreading at least from 660 Ma to 600 Ma in the Macaúbas basin (Figure 7).

The Jequitinhonha Complex (see Figure 1), consisting of Al-rich paragneiss, quartzite, graphite gneiss, and calc-silicate rocks exposed in the northern portion of the orogens (crystalline core), is currently viewed as correlative of the passive margin deposits of the Cryogenian upper Macaúbas Group [177,178].

The Salinas Formation consists of a ca. 1600 m thick succession of turbiditic wackes, sandstones, pelites, and conglomerates interpreted as a syn-orogenic assemblage accumulated between 548 and 520 Ma. The detrital zircon age spectra of the Salinas Formation [45,150,179] indicate that its main sources were the Rio Doce magmatic arc and the Paleoproterozoic basement units. The vertical facies changes in the whole Salinas Formation characterize a coarsening upward first-order sequence that records a general southwest–south progradation of a turbidite fan system fed from the north [180].

Developed between 620 and 580 Ma during the pre-collisional stage of the Araçuaí orogen, the Rio Doce magmatic arc is materialized by granitoids of the G1 Supersuite and volcano–sedimentary rocks of the Rio Doce Group [147,150,181–183], which occur in the crystalline core. The syn to late collisional intrusions are grouped in the G2 Supersuite, which comprises S-type peraluminous granites dated between 590 and 540 Ma [184]. The post-collisional granites characterize two distinct assemblages, the G4 and G5 Supersuites, which consist of 530–500 Ma leucogranites and 520–480 Ma high-K metaluminous I-type granitoids, respectively [184]. In this region, the Araçuaí orogen comprises a stack of allochthons containing large volumes of anatectic and magmatic rocks resulting from partial melting of the middle crust [185,186].

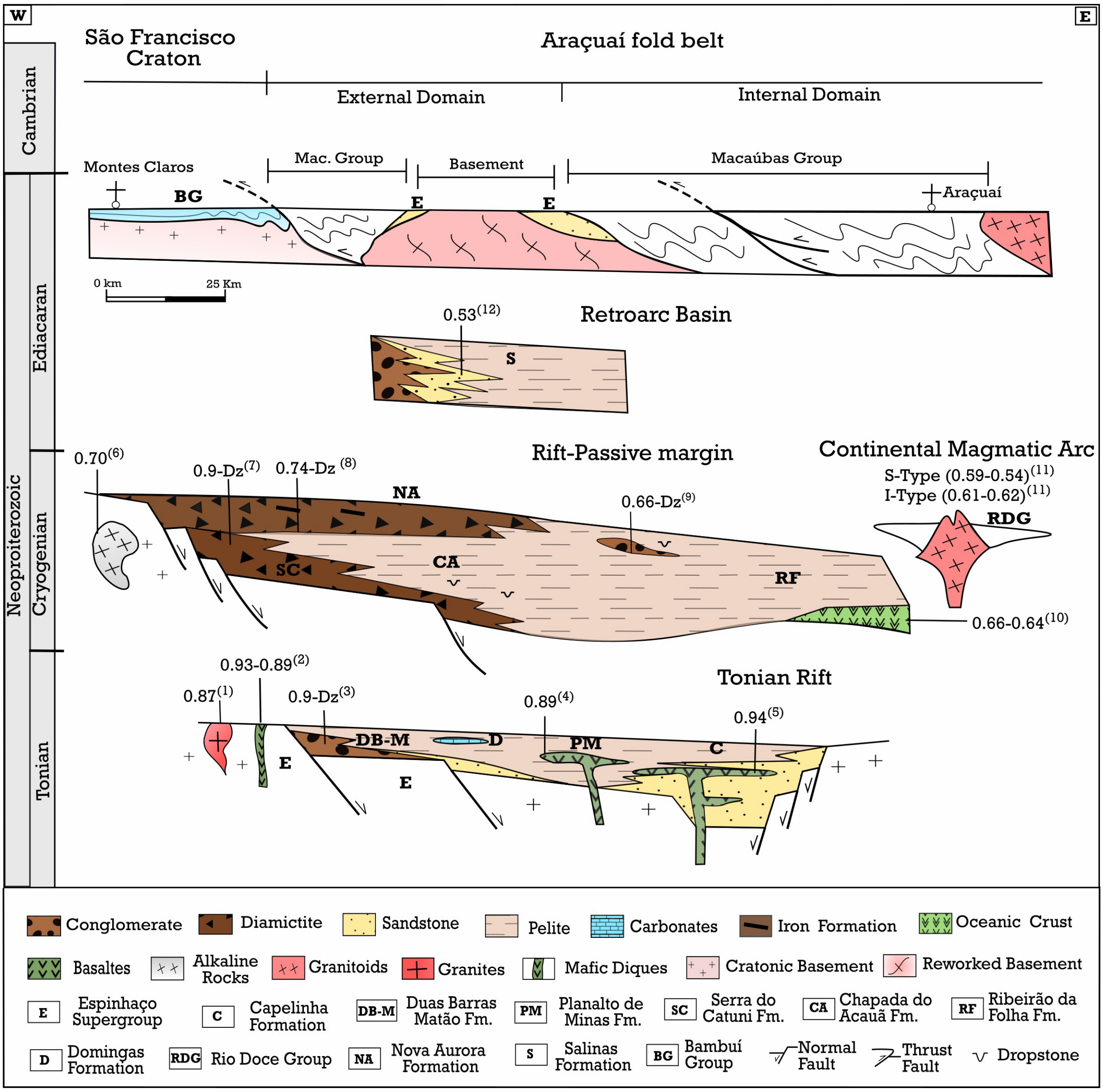

Figure 7. The Araçuaí Belt: sedimentary basins, extensional and contractional events, and geological evolution [147,149–151,184]. Geochronological data: 1—[162]; 2—[159–161]; 3—[156–158]; 4—[166]; 5—[165]; 6—[167]; 7—[157]; 8—[158]; 9—[171,172]; 10—[173,174,176]; 11—[181–184]; 12—[45,150,179]. Dz: Detrital zircon.

The Araçuaí belt is dominated by a system of folds, thrusts, and reverse folds that verge toward the adjacent São Francisco craton. Rocks involved in the Araçuaí belt exhibit metamorphic paragenesis characteristic of the greenschist and amphibolite facies. Three main sectors and domains can be recognized in the belt [149]: (1) the Espinhaço-Macaubas fold–thrust belt with E-dipping foliation associated with a down-dip stretching lineation;

(2) Rio Pardo salient, the large antitaxial curve along the craton southeastern margin, the interference zone with the Paramirim Corridor (reverse to oblique-slip faults of opposite vergences), and the WNW-trending dextral Itabepi shear zone at northeast; and (3) transitions to Ribeira Belt with dextral shear zone and associated structures at southest [149,151]. The remarkable Chapada Acauã Extensional Shear Zone is characterized by overall normal motion toward ESE (gravitational collapse) with ESE-verging folds, a regionally pervasive WNW-dipping crenulation cleavage [187]. The main collisional event (~580–520 Ma) developed reverse faults and overtaking with transport to the west and lateral escape phases with shear zones and gravitational collapse, also generating great deformation in the Paramirim Corridor.

The subduction–collision Araçuaí orogen model was recently contested and questioned [188]. They argue that (1) there is an oceanic space problem in this confined setting model; (2) oceanic crust evidence are dubious; (3) there is a problem with the subduction initiation; (4) high-P metamorphism records are not found; and (5) there is a problem with the abrupt termination of an ocean with no realistic way to transfer the large amount of oceanic opening displacement and subsequent convergence required by the model. They suggest that the existing data are more consistent with a hot intracontinental orogeny [188]. However, those authors do not discuss the abundant elemental and isotopic geochemical data that strongly suggest the consumption of an oceanic domain in the Araçuaí Orogen and in the southern extension of the Mantiqueira Province [189].

8. Discussions

The São Francisco craton is surrounded by several Neoproterozoic orogens and fold belts. We identified different sedimentary basins in the orogens, which were deformed at the end of the Brasiliano cycle. Geochronological data of deformation and metamorphism provide constraints for the sequence of collision events that led to the formation of the West Gondwana supercontinent. The assembly was diachronous and occurred in important three-stage Neoproterozoic–Cambrian collision processes (Figure 8).

The Southern Brasília belt (Figure 2) presents the development of the Tonian Araxá-Canastra-Vazante passive margin and Tonian–Cryogenian intraoceanic magmatic arcs with arc-related sedimentary basins [38,50,190]. Progressively, the intraoceanic scenario evolves to an arc–continent collision in Cryogenian time. During the late Cryogenian, a retroarc basin (Araxá and Ibiá Groups) occurs, with gravitational sedimentation within a deep submarine fan, which transitions to the gravitational and glacial sedimentation of the Vazante Group (Santo Antônio do Bonito and Rocinha Formations) and Jequitaí Formation to the east, toward the São Francisco paleocontinent [24,31,43]. Thus, the Southern Brasília Belt shows different basin settings overlapping in time: Tonian passive margin and arc-related basins to Cryogenian–Ediacaran retroarc foreland basin (Ibiá Group) and Ediacaran-Cambrian peripheral foreland basin (Bambuí Group). The Southern Brasília belt consists of numerous east- to southeast-verging spoon-shaped nappes of high-grade gneiss, granulite, schist, and quartzite. The southern Brasília belt depicts the first paleocontinents collision and involved the southern São Francisco–Congo and Paranapanema cratons, which generated the east-verging nappes. The metamorphism is dated between 650 and 620 Ma, with the generation of S_1-S_2 penetrative subhorizontal ductile foliation and the development of metamorphic minerals [14,15,19,190,191].

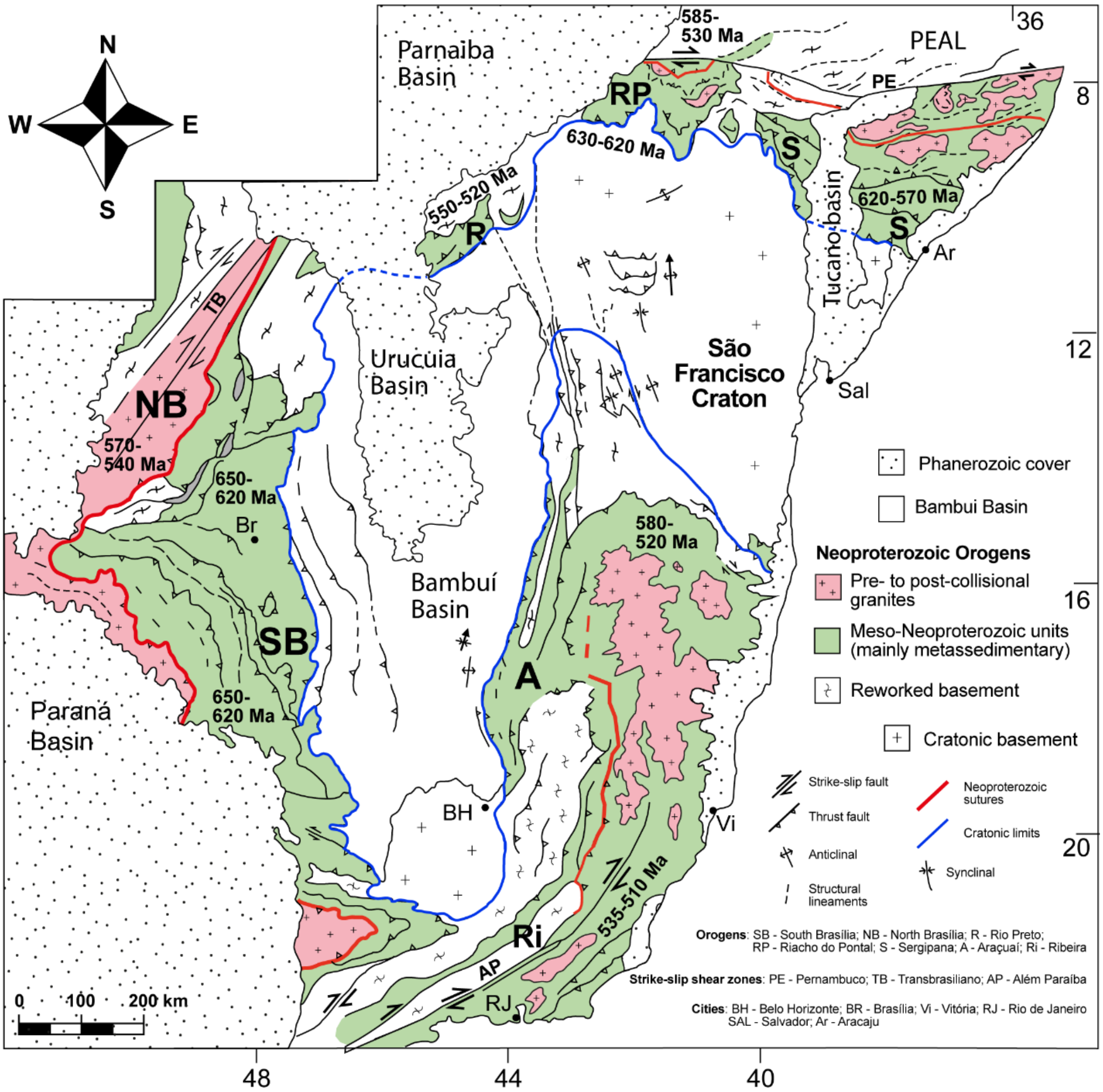

Figure 8. Simplified tectonic map of the central–eastern region of Brazil with an indication of the three collisional diachronic events in the formation of the SF Craton: Brasília Belt (collision I: 650–620 Ma), Riacho do Pontal–Sergipano Belt (collision II: 620–570 Ma) and Araçuaí Belt (collision III: 580–520 Ma) (see text). Modified from [9,192].

The Northern Brasília belt (Figure 3) is an east- to southeast-verging fold–thrust belt that involves Archean basement, Paleo-Mesoproterozoic rift (Araí Group) and rift-sag basins (Serra da Mesa and Traíras Groups), a Stenian passive margin (Paranoá Group) with the Juscelândia, Indaianópolis and Palmeirópolis volcanosedimentary sequences. During the Ectasian-Stenian, the Paranoá passive margin develops, strongly asymmetrical, associated with an important extensional phase, filled by sandstones, pelites, rhythmites, and carbonates lenses with columnar stromatolites, arranged in transgressive and regressive cycles [14,70,72]. The Stenian passive margin is related to the deposition of the Paranoá Group sediments and probably the volcano–sedimentary sequences that show ocean floor basalts (MORB) [14,75]. Neoproterozoic supracrustal units in the northern Brasília belt are uncommon. Neoproterozoic rocks in the Northern Brasília belt are the Tonian–Ediacaran intraoceanic to the continental magmatic arc of Mara Rosa and the Tonian Mafic–Ultramafic Complexes of Barro Alto, Cana Brava, and Niquelândia (790 Ma) [49,63,77,79,80]. During the Neoproterozoic, oceanic lithosphere was consumed along possible west-dipping subduction zones, and the island arc systems were accreted to the western margin of the São Francisco paleocontinent at 770–750 Ma [47,63]. The northern Brasília belt shows two tectonic phases. The first (D_1) is a SE-verging fold–thrust belt with S_1 foliation and stretching lineation toward azimuth 280–290, represented by the thrust system of the Maranhão River [16,85]. It is associated with the regional metamorphism and occurred between 650 and 610 Ma. The D_2 phase is transpressive and is a high-grade, ductile, dextral, strike-slip shear zone associated with the Transbrasiliano lineament (TB), related to the collision between the Amazonian craton and São Francisco craton between 580 and 540 Ma [87,193]. At its southern end, the Northern Brasília belt overlaps the Southern Brasília belt forming a pronounced syntaxis—the Pireneus syntaxis [20].

To the north of the São Francisco craton, the Rio Preto, Riacho do Pontal, and the Sergipano belts are separated from each other by basement highs. The Rio Preto belt shows the Canabravinha Formation was deposited into an asymmetrical rift basin (hemi-graben basin) with gravitational flows and turbiditic sediments (Figure 4). The belt is interpreted as an intracontinental rift at the termination of the Riacho do Pontal and Sergipano orogens. Neoproterozoic–Cambrian deformation, between 550 and 520 Ma, originated a complex, asymmetrical, and double-verging thrust wedge associated with the northwest curvature of the SFC [93]. The Riacho do Pontal and Sergipano belts (Figures 5 and 6) contain south-verging thrusts involving basement rocks older than 1.8 Ga, Tonian and Cryogenian rift-related units (Brejo Seco, Miaba and Canindé rifts), Cryogenian passive margin assemblages (Casa Nova Group, Monte Orebe ophiolitic rocks, Vaza Barris and Macururé Groups) and Ediacaran continental magmatic arcs [93,100,101,109,124,125]. Convergence and collision of the PEAL block (upper plate) with the São Francisco-Congo paleocontinent (lower plate) caused deformation and metamorphism of passive margin sedimentary successions, with stacking of the Casa Nova nappes upon the lower plate, crustal thickening, and syn-collisional granite emplacement in the Riacho do Pontal and Sergipano orogens, between 620 and 560 Ma. The lateral escape phase occurred around 585–530 Ma, generating the western branch of the E-W trending dextral Pernambuco shear zone, which truncates the northern part of the Sergipano orogen. This phase was accompanied by extensive alkaline magmatism of the Serra da Aldeia Suite, dated at 586–576 Ma [93,101]. South-verging thrusts of the Riacho do Pontal and Sergipano belt propagated southward into the Chapada Diamantina region (northeastern São Francisco craton). The Riacho do Pontal—Sergipano belts are related to a second collision event involving the São Francisco–Congo paleocontinent and the PEAL block (620–560 Ma).

The Araçuaí belt (Figure 7) that fringes the southeastern São Francisco craton contains west-verging thrusts and folds. In the Araçuaí belt, there are Neoproterozoic rocks of the Macaúbas Group, forming the intracontinental Tonian rift and the Cryogenian–Ediacaran passive margin of Serra do Catuni, Chapada Acauã, Nova Aurora, and Ribeirão da Folha formations. Furthermore, there is the Ediacaran continental arc Rio Doce Group and the forearc Salinas basin [45,147,150,151]. The Macaúbas basin is dominantly a large continental rift with steep N-S and NW-SE normal fault edges. To the southeast, due to differential extension, the basin evolved as a localized passive margin with oceanic crust. The crustal extension was accommodated by E-W transfer faults. Reactivations at the edges of the Macaúbas rift gave rise to thick gravitational sedimentation, with cohesive debris flow (diamictites) and turbidity currents (sandstones and pelites) and glacial influence [169,171,172], during the early and late Cryogenian. These units of the Macaúbas Group, exposed along the belt, were metamorphosed under greenschist to amphibolite facies conditions and were affected by thrusts, reverse faults, and craton-ward verging folds, developed between 575 and 530 Ma [149,151]. The Araçuaí orogenic front propagates into the craton interior and interacts with preexistent rift structures, affecting rocks within the Paramirim corridor. To the southern, the Ribeira belt was deformed between 610 and 560 Ma [9,18,194], with the docking of the Cabo Frio terrane at 535–510 Ma [195]. The northern Ribeira belt is characterized by a 500 km long network of anastomosing transcurrent shear zones parallel to the belt. A northeast–trending dextral transpressive belt is interpreted as a later oblique convergence between the São Francisco Craton and Congo Craton [196]. NE-trending, dextral strike-slip shear zones with late collisional leucogranites, pegmatites, and hydrothermal fluids are dated at 535–510 Ma [194]. The Araçuaí orogen is related to a third collisional event in central-east Brazil, between São Francisco and Congo cratons at 580–530 Ma (Figure 8).

Paleogeographic maps are presented at the end (Figure 9), illustrating the diachronic evolution of Neoproterozoic orogens around the São Francisco-Congo (SF-C) paleocontinent. A large Tonian–Cryogenian ocean occurred to the west, with amalgamated intraoceanic magmatic arcs (Brasília belt). To the north (Riacho do Pontal-Sergipano belt) and south (Araçuaí belt), small v-shaped oceans with hyperextended margins occurred, with Ediacaran continental magmatic arcs [197].

In the Stenian–Tonian, a large ocean (Goiás Ocean) formed on the western side of the São Francisco–Congo paleocontinent, with passive margin basins made up of the Paranoá (to the north) and Vazante–Canastra–Araxá (to the south) Groups and extended continental margins (Figure 9A). In the Tonian, compression on the western margin generated subduction zones and intraoceanic island arcs, forming primitive calc-alkaline granitoids [16,49]. On the other hand, on the northern margin of the paleocontinent, extension generated an extended continental margin, the Brejo Seco rift, with mafic–ultramafic plutonic rocks of the Brejo Seco Complex and sedimentary and volcanic rocks of the Paulistana Complex [93,101]. To the southeast of the SF paleocontinent, a Tonian rift formed [151,165,166], with continental and marine sediments and basaltic volcanics (Figure 9A), partly connected to the ocean floor of the Ribeira basin (Adamastor Ocean [194,197]).

During the Tonian–Cryogenian (Figure 9B), the intra-oceanic arcs of the western margin amalgamated in successive phases, and there was also local extension with rift generation and intrusion of mafic–ultramafic plutonic rocks at 790 Ma [49,77]. Extension on the northern margin increases with evolution to the Riacho do Pontal passive margin, made up of the Barra Bonita Formation (southern margin), the Santa Filomena Complex (northern margin), and the oceanic crust of the Monte Orebe Complex [101,113]. To the SW there is an extension and formation of the Rio Preto rift or aulacogen. To the east, there is a transition to the Canindé rifts (sedimentation with basic volcanism and mafic–ultramafic plutonism [125,139] and the Miaba rift or aulacogen, with detrital sedimentation and glacial influence. To the southeast, there is extensive rift sedimentation of the Macaúbas and W-Congo basins in the Cryogenian, with glacial influence [147,149].

In the Cryogenian–Ediacaran (Figure 9C), continental magmatic arcs developed in the Brasília orogen, evolving to a continental collision between the Paranapanema and SF paleocontinents and the Goiás microcontinent, with closure of the Goiás Ocean [47,49]. Retroarc foreland basins occur in the southern portion of the Brasília orogen (e.g., Ibiá Group), based on the occurrence of debris from the continental magmatic arc. To the north, in the Cryogenian, the passive margin basin involving the Riacho do Pontal and Sergipano orogen expands, with subduction beginning at 630–620 Ma (Ediacaran) and the formation of continental magmatic arcs next to the PEAL [101]. To the southeast, the extension involves the formation of oceanic crust (650–630 Ma) located in the Macaúbas basin (locally passive margin) and also the Rio Doce Cordilleran magmatic arc (620 Ma) [147,151,176].

In the Ediacaran–Cambrian (Figure 9D), there were continental collisions to the north between the PEAL and SF paleocontinents, generating the Riacho do Pontal and Sergipano orogens and lateral escape in the Pernambuco shear zone [101,193]. There was also a continental collision between the Amazonian and São Francisco–Congo paleocontinents, generating deformation in the northern Brasília orogen (Transbrasiliano shear zone [87]). Finally, a collisional event between the SF and Congo paleocontinents, with deformation in the Macaúbas, West Congo, and Ribeira basins and closure of the Adamastor Ocean [149,194].

Extensional tectonics generated hyperextended continental margins, rifts, and large and small V-shaped ocean basins and microcontinents [197]. Compression generated Tonian–Cryogenian intra-oceanic island arcs and Ediacaran continental magmatic arcs that evolved via collisions with paleocontinents, generating various Neoproterozoic orogens forming the Western Gondwana.

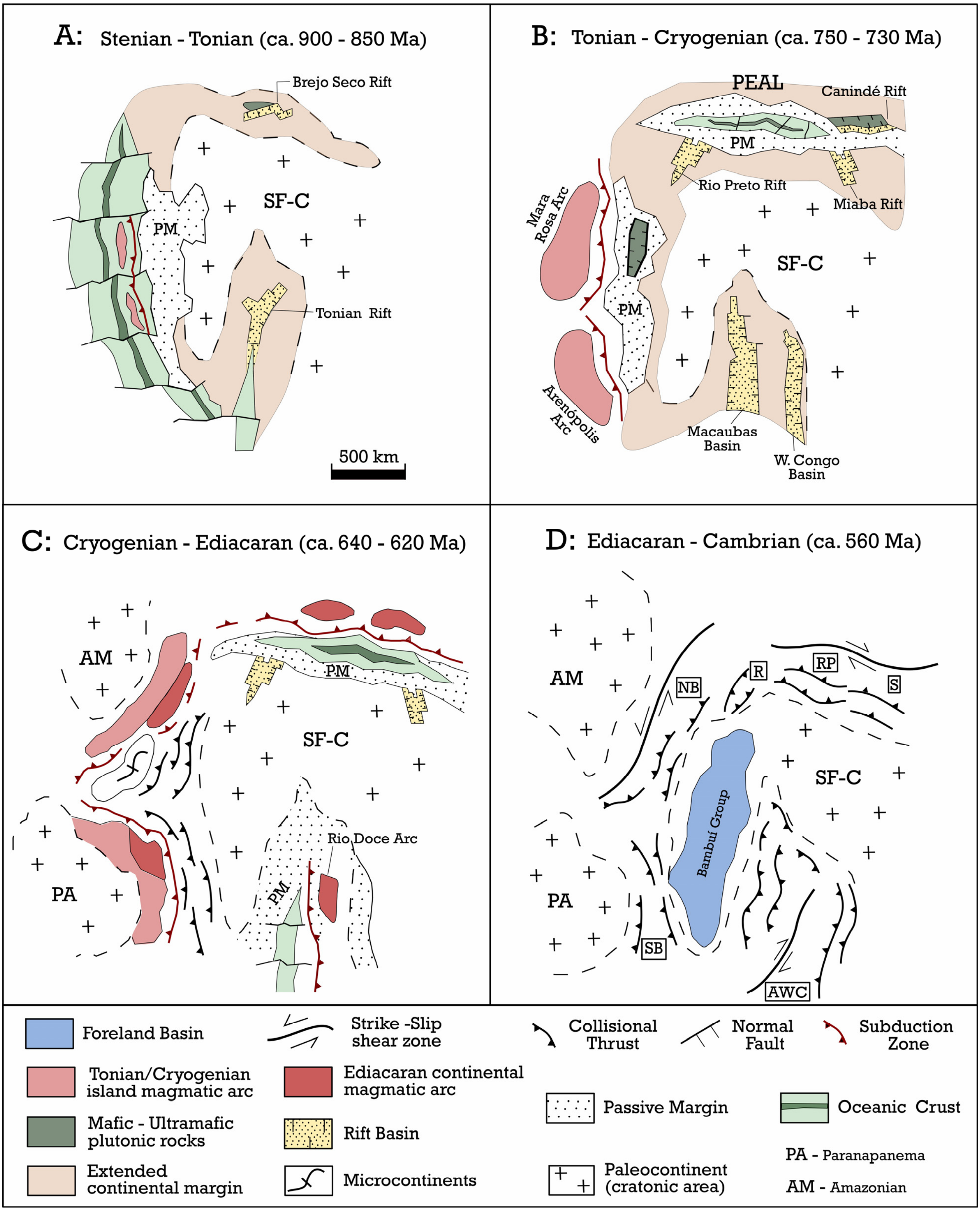

Figure 9. Simplified paleogeographic maps illustrating the diachronic evolution of the orogens around the São Francisco–Congo (SF-C) paleocontinent during the Neoproterozoic. Explanations for each subfigure are given in the Discussion chapter.

9. Conclusions

The São Francisco craton (SFC) is surrounded by several Neoproterozoic orogens: the Southern and Northern Brasília belt (west), the Rio Preto–Riacho do Pontal–Sergipano belt (north), and the Araçuaí–Ribeira belt (southeast).

The Southern Brasília belt presents the development of the Tonian Araxá–Canastra–Vazante passive margin and Tonian–Cryogenian intraoceanic magmatic arcs with arc-related sedimentary basins. The Southern Brasília belt also shows different basin settings overlapping in time: the retro arc foreland basin (Ibiá Group) and peripheral foreland basin (Bambuí Group) in the Ediacaran–Cambrian. The Southern Brasília belt consists of numerous east- to southeast-verging spoon-shaped nappes of high-grade gneiss, granulite, schist, and quartzite. The Southern Brasília belt depicts the first paleocontinent collision and involved the southern São Francisco–Congo and Paranapanema cratons, generating east-verging nappes at 650–620 Ma, with the generation of S_1–S_2 penetrative foliation.

The Northern Brasília belt is an east- to southeast-verging fold–thrust belt that involves the Archean basement, Paleo-Mesoproterozoic rift (Araí Group) and rift–sag basins (Serra da Mesa and Trairas Groups), a Stenian passive margin (Paranoá Group), and Juscelândia, Indaianópolis and Palmeirópolis volcanosedimentary sequences. Neoproterozoic rocks in the Northern Brasília belt are the Tonian–Ediacaran intraoceanic to the continental magmatic arc of Mara Rosa and the Tonian Mafic–Ultramafic Complexes of Barro Alto, Cana Brava, and Niquelândia (790 Ma). The Northern Brasília belt shows two tectonic phases: (1) an SE-verging fold–thrust belt with S_1 foliation and stretching lineation represented by the thrust system of the Maranhão River at 640–610 Ma; and (2) a ductile, dextral, strike-slip shear zone associated with the TransBrasiliano lineament (TBL), which is related to the collision between the Amazonian and São Francisco cratons between 580 and 540 Ma.

The Rio Preto–Riacho do Pontal–Sergipano belts occur in the northern limit of the São Francisco craton. The Rio Preto belt is interpreted as an intracontinental rift, deformed at 540–520 Ma, showing a complex, asymmetrical, and double-verging thrust wedge whose southern branch propagated for over 100 km into the craton. The Riacho do Pontal-Sergipano belts contain south-verging thrusts involving basement rocks older than 1.8 Ga, Tonian and Cryogenian rift-related units (Brejo Seco, Miaba, and Canindé rifts), Cryogenian passive margin assemblages with ophiolitic rocks (Monte Orebe, Vaza-Barris, Macururé) and Ediacaran continental magmatic arcs. Convergence and collision of the PEAL block (upper plate) with the São Francisco–Congo paleocontinent (lower plate) caused deformation and metamorphism of the passive margin sedimentary successions between 620 and 560 Ma. The lateral escape phase occurred at approximately 585–530 Ma, generating the western branch of the E-W trending dextral Pernambuco shear zone. The Riacho do Pontal—Sergipano belts are related to a second collision event involving the São Francisco–Congo paleocontinent and the PEAL block, which generated south-verging nappes and thusts (620–560 Ma).

The Araçuaí belt that fringes the southeastern São Francisco craton there are Neoproterozoic rocks of the Macaúbas Group, forming the intracontinental Tonian rift, and the Cryogenian-Ediacaran passive margin of Serra do Catuni, Chapada Acauã, Nova Aurora and Ribeirão da Folha Formations. Furthermore, there is the Ediacaran continental arc Rio Doce Group and the retroarc Salinas Basin. These units, exposed along the belt, were metamorphosed under greenschist to amphibolite facies condition and were affected by thrusts, reverse faults, and craton-ward verging folds, developed between 575 and 530 Ma. The Araçuaí orogenic front propagates into the interior of the craton and interacts with pre-existing rift structures, affecting rocks within the Paramirim corridor. The Araçuaí orogen is related to a third collisional event in central–east Brazil, between the São Francisco and Congo cratons at 575–530 Ma.

10. Suggestions for Future Research

In the Southern Brasília Belt, which consists of several overlapping Neoproterozoic basins, a precise characterization of the metasedimentary lithotypes is important, in addition to geochemical, geochronological, and sedimentary provenance studies using modern methods. The phase of Tonian intra-oceanic island arcs evolving into arc-continent collision at the end of the Cryogenian is still poorly understood and deserves to be highlighted in future work.

The Northern Brasília Belt has important stratigraphic, geochronologic, and geotectonic differences from the Southern Brasília Belt. It should be studied independently of the southern segment. It could be given a different name, such as the Rio Maranhão Belt. In this context, the passive margin basin and the Neoproterozoic magmatic arc basins are still poorly known in the evolution of the belt. Do the Mesoproterozoic volcanosedimentary sequences and the Paranoá Group form a passive margin basin, then separated by compressive tectonics?

In the northern belt, Rio Preto, it is important to carry out U-Pb geochronology of the Riachão das Neves Formation (correlated with the Três Marias Formation) to better date the structural evolution of the belt and also of the Canabravinha Formation, aiming at comparison with other diamictite-bearing units. A regional and integrated study of the Riacho do Pontal and Sergipano belts is important, with the identification of ophiolitic complexes and volcanosedimentary sequences of the magmatic arc. Also, a comparative stratigraphic and geochronologic study between the well-exposed glacial sequences in the Sergipano Belt (Miaba and Vaza Barris Groups) could better correlate with global glacial events.

In the Araçuaí Belt, a comparative study between the different Neoproterozoic sedimentary basins, especially the Cryogenian–Ediacaran rift–passive margin transition and the glacial influence on sedimentation (one or two global glaciations) would certainly be relevant. In addition, a systematic comparison is suggested between the intracontinental northern Araçuaí Belt, a rift basin that transitions into the Paramirim corridor, with the southern part of the Araçuaí Belt, which is accretionary, with a passive margin and small oceanic crust, and also the Rio Doce magmatic arc. In the Paramirim Corridor, in the central region of the SF Craton, it is still necessary to better individualize the Neoproterozoic sedimentation (Santo Onofre Formation or Group), to correlate it with the Macaúbas Group and to evaluate the magnitude of the Pan-African–Brasiliano deformation in the region.

Finally, future research projects would be to compare these folded belts around the SF craton with the belts around the Amazon Craton in Brazil and also with the belts around the African cratons-West Africa (to the north), Congo, and Kalahari (to the south).

Author Contributions: Conceptualization, investigation, writing—original draft preparation, A.U.; writing—review and editing, G.J.U., F.d.A.C. and S.A.M. All authors have read and agreed to the published version of the manuscript.

Funding: The authors received financial support from Brazilian Research Foundations FAPEMIG (Fundação de Amparo à Pesquisa do Estado de Minas Gerais), grant APQ-02240-21, and CNPq (Conselho Nacional de Desenvolvimento Científico e Tecnológico), grants 432556/2018-4 and 305780/2018-2.

Data Availability Statement: Available datasets were analyzed in this study. The data can be found in the cited papers.

Acknowledgments: The authors are grateful to the support of Universidade Federal de Minas Gerais and its Dean of Research (PRPq), the Instituto de Geociências, and the Centro de Pesquisas Professor Manoel Teixeira da Costa (CPMTC). In addition, fruitful discussions with Roland R. Trompette, Marcos Egydio-Silva (Universidade de São Paulo-USP), Hildor J. Seer (Centro Federal de Educação Tecnológica de Minas Gerais, CEFET-Araxá), Carlos J.S. de Alvarenga, Elton L. Dantas, and Cesar F. Ferreira Filho (Universidade de Brasília-UnB) improved the final manuscript. The first version of the manuscript was significantly improved by the review of three anonymous reviewers. We are also grateful to Alexandru G. Calin for editorial assistance.

Conflicts of Interest: The authors declare no conflicts of interest.

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