The Rio Preto and Riacho do Pontal Belts

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Abstract

Together, the Rio Preto and Riacho do Pontal belts form a 600 km-long orogenic system developed along the northwestern and northern margins of the São Francisco craton during the Neoproterozoic Brasiliano orogeny. Involving the Paleoproterozoic ($\sim$1.9 Ga) Formosa Formation (schist, quartzite, greenschist and amphibolite) and the Neoproterozoic (900–600 Ma) Canabravinha Formation (metadiamictite, metawacke, metaturbidite), the Rio Preto fold belt, exposed in Bahia and Piauí states, borders the craton to the northwest. Neoproterozoic deformation between 600 and 540 Ma originated a complex, asymmetrical and double-verging thrust wedge, whose southern branch propagated for over 100 km into the craton interior in form of a thin-skinned deformation front. The Rio Preto belt probably represents an inverted Neoproterozoic hemi-graben developed along the northern margin of the craton. The Riacho do Pontal fold belt occupies the northern margin of the craton. Its external zone is made up of a south-verging thin-skinned nappe system detached along the basement-cover contact. Ages of syn- to late-collisional granitic intrusions suggest that the main deformation phase in the Riacho do Pontal belt occurred between 667 and 555 Ma. The Barra Bonita Formation (quartzite, schist and marble), a correlative of the Una Group in craton interior (Paramirim aulacogen), represents a platformal unit, deposited on the northern São Francisco passive margin. The Monte Orebe metabasalts, exposed further north in the central sector of the belt, might represent remnants of a Neoproterozoic oceanic crust.

Keywords

Rio Preto belt • Riacho do Pontal belt • Brasiliano orogeny • Neoproterozoic • Basin inversion • Passive margin basin

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12.1 Introduction

The Rio Preto and Riacho do Pontal belts form together a 600 km-long orogenic system developed along the north and northwest margins of the São Francisco craton (Fig. 12.1). In the context of the fold-thrust belts that surround the craton and Brasiliano systems in general, the Rio Preto and Riacho do Pontal represent the least studied orogenic zones.

In this chapter, we present a synthesis on the state-of-the art of the geological understanding of each of these fold belts, exploring the stratigraphic and structural relations between them and the adjoining cratonic area (Table 12.1). In order to establish links to the adjacent cratonic domain, the descriptions provided here focus mainly the external zones of each belt, rather than their internal sectors.

12.2 The Rio Preto Belt

12.2.1 Stratigraphy

12.2.1.1 Basement Units

The basement (Figs. 12.2 and 12.3), exposed in the northern and more internal portions of the belt, is represented by the Cristalândia do Piauí Complex (Arcanjo and Braz Filho 1994), composed of biotite and hornblende orthogneisses with amphibolite intercalations. The regional dominant structure is a southeast-dipping gneissic foliation, which transposes older structures and parallels the axial-plane of isoclinal folds. Available geochronological data suggest either crystallization or metamorphism around 2.1 Ga (Rb-Sr whole-rock isochron). K-Ar geochronological deter-

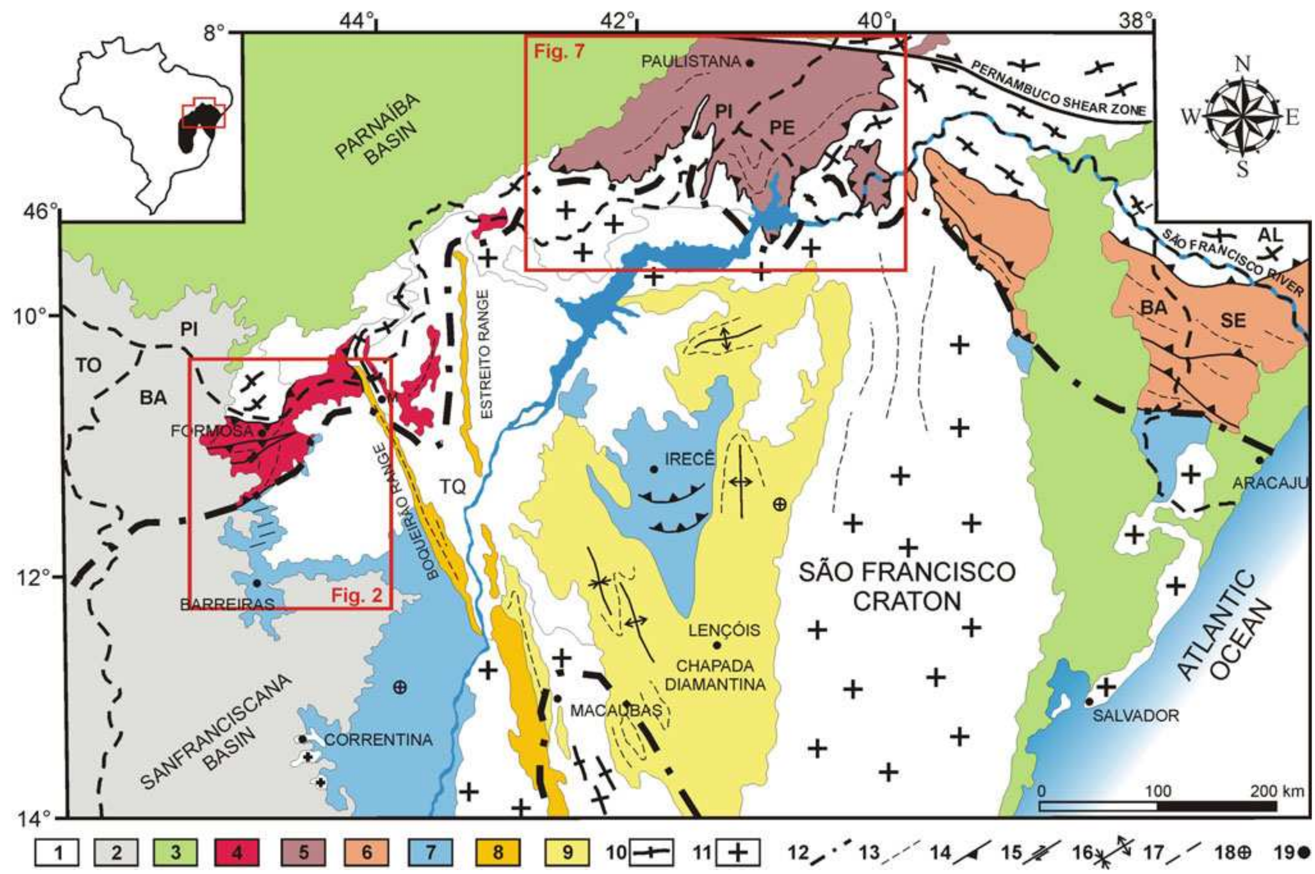


Fig. 12.1 Simplified geologic map of the northern São Francisco craton and its marginal fold belts (modified from Uhlein et al. 2011; 2012). *1*—Cenozoic covers; *2*—Cretaceous Urucuia Group; *3*—Paleo and Mesozoic basins; Northern São Francisco Craton marginal fold belts: *4*—Rio Preto; *5*—Riacho do Pontal; *6*—Sergipana; Proterozoic covers of the São Francisco Craton: *7*—Bambuí Group and correlatives; *8*—Santo Onofre Group; *9*—Espinhaço Supergroup; Archean/Paleoproterozoic basement: *10*—Reworked basement within the orogenic domain; *11*—São Francisco Craton basement; *12*—Craton/fold belt boundary; *13*—Structural lineaments; *14*—Thrust; *15*—Strike-slip shear zone; *16*—Synclinal/anticlinal axis; *17*—Interstate border; *18*—Horizontal bedding; *19*—City

Table 12.1 Comparative stratigraphy of the Rio Preto and Riacho do Pontal fold belts and adjoining cratonic areas

Age	Rio Preto belt	NW São Francisco Craton	Riacho do Pontal Belt		Northern São Francisco Craton
			Volcanosedimentary sequences	*Plutonic suites*	
Ediacaran/Cambrian (ca. 630–530 Ma)		Bambuí Group	Mandacaru Formation	Serra da Aldeia/Caboclo Suite	Una Group
				Serra da Esperança Suite	
				Rajada Suite	
Cryogenian/Early Ediacaran (ca. 820–630 Ma)	Canabravinha Formation		Barra Bonita Formation		
			Monte Orebe Complex		
Late Tonian/Early Cryogenian (ca. 900–820 Ma)			Paulistana Complex	Brejo Seco Complex	
				São Francisco de Assis Complex	
Early Tonian (ca. 1000–960 Ma)			Morro Branco Complex Santa Filomena Complex (?)	Afeição Suite	
Archean/Paleoproterozoic	Formosa Formation	Basement in the Correntina region	Morro do Estreito Complex		São Francisco craton basement and Paleoproterozoic covers
	Cristalândia do Piauí Complex				

minations on biotite crystals yielded ages around 540 Ma (Egydio-Silva 1987). Recent published Sm–Nd model ages (T_{DM}) between ca. 2.8 and 2.6 Ga suggest that an Archean crust is the main component of this segment of the basement (Caxito 2010; Caxito et al. 2014a). Altogether, the data suggests the imprinting of a Rhyacian tectono-metamorphic event upon an Archean continental crust, followed by the resetting of the K-Ar clock during the Brasiliano orogeny.

The Formosa Formation (Figs. 12.2 and 12.4) corresponds to the Rio Preto Group of Egydio-Silva et al. (1989), as redefined by Caxito et al. (2012a). This unit crops out in the northern portion of the belt, alongside the Preto river valley, extending for ca. 20 km towards north, reaching the region of the boundary between the states of Bahia and Piauí (Figs. 12.2 and 12.3). It is composed of muscovite schists, often garnet-rich, with layers of micaceous quartzite, sandy metarhythmite, iron-manganese metachert (the guide-layer of the unit), chlorite-actinolite-epidote schist (greenschist), and, locally, ortho-amphibolite intercalations. The latter are 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 the mica schists of the Formosa Formation. Caxito (2010) and Caxito et al. (2015) conducted a petrographic, geochemical, isotopic and geochronological study on these amphibolites and interpreted them as tholeiitic gabbros metamorphosed under epidote-amphibolite facies conditions (around 500 °C and 2–5 kbar). Flat chondrite-normalized rare earth elements (REE) patterns and slight enrichment of light REE compared to heavy REE (La_N/Yb_N: 1.35–2.97; Eu/Eu*: 0.94–1.14), negative Nb and positive Sr anomalies, as well as high LIL/HFS ratio suggest an hybrid of mid-ocean ridge and island arc environments, probably reflecting a back-arc setting (Caxito 2010; Caxito et al. 2015). U-Pb analyses of magmatic zircon crystals (Th/U: 0.11–1.56) yielded a precise age of 1958.3 ± 16 Ma, with $\varepsilon Nd_{(1.96)}$ ranging from slightly negative to positive values (−0.3 to +1.0), suggesting variable mixing of a depleted mantle source and older continental crust (Caxito et al. 2015).

Studies on the detrital zircon record indicates a relatively monotonous sedimentary provenance for the Formosa Formation, with bimodal distribution of detrital zircon U-Pb ages between 1.9–2.2 and 2.5–2.6 Ga. T_{DM} model ages between 1.9 and 2.6 Ga corroborate the provenance data (Caxito 2010; Caxito et al. 2014a), indicating that the

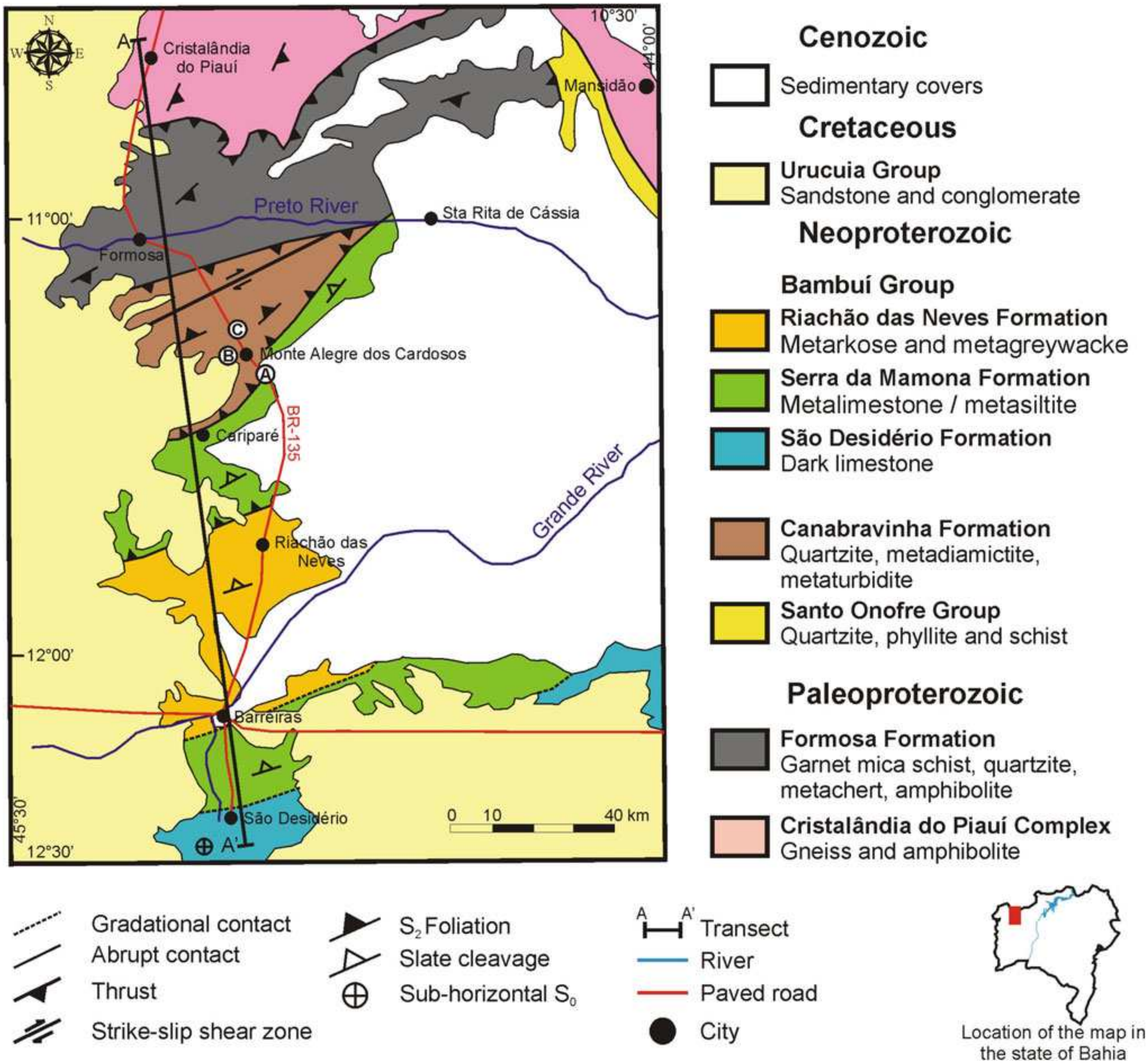


Fig. 12.2 Simplified geologic map of the Rio Preto fold belt and adjacent northwestern São Francisco craton (modified from Egydio-Silva 1987; Egydio-Silva et al. 1989; Caxito 2010)

basement assemblage of the Cristalândia do Piauí Complex was the main source for the Formosa Formation. The absence of Mesoproterozoic and Neoproterozoic zircons and the intercalation of Paleoproterozoic mafic rocks suggest that at least part of the Formosa Formation was deposited during the Paleoproterozoic ($\sim$1.96 Ga ago), probably in a basin related to a magmatic arc.

The Formosa Formation it is thrust northward over the gneisses of the Cristalândia do Piauí Complex. The south contact with the Canabravinha Formation is made by a reverse-dextral shear zone (Malhadinha-Rio Preto Shear Zone, Gonçalves Dias and Mendes 2008; Caxito et al. 2014b). The Formosa Formation is thrust on top of the quartzites of the Santo Onofre Group along the Boqueirão ridge on the east (Egydio-Silva 1987) (Figs. 12.2 and 12.3). The main Neoproterozoic regional structure affecting this unit is a Neoproterozoic crenulation cleavage (S_2). Rocks exhibiting this cleavage have yielded muscovite K-Ar ages between 600 and 540 Ma (Egydio-Silva 1987).

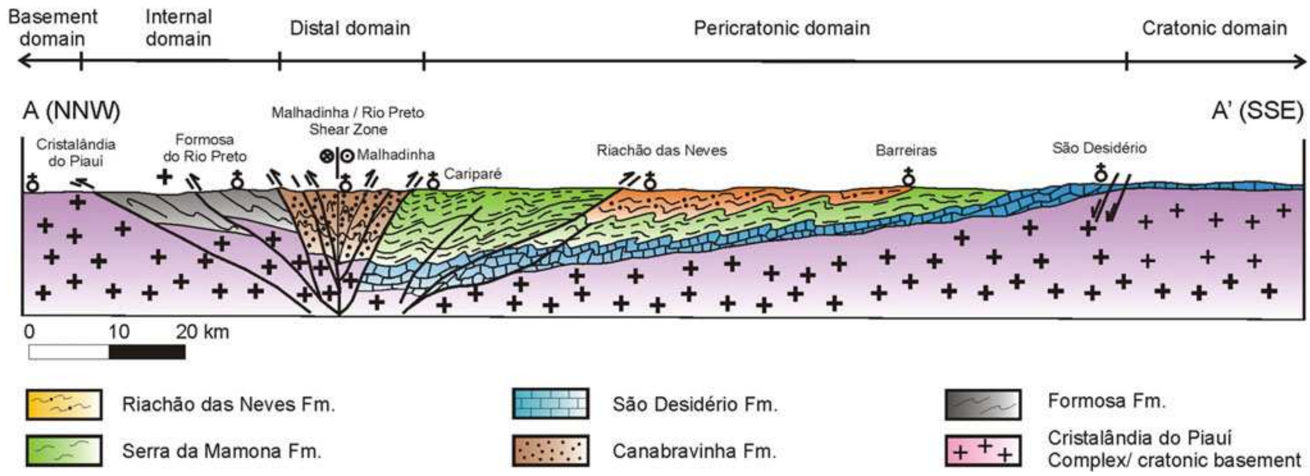
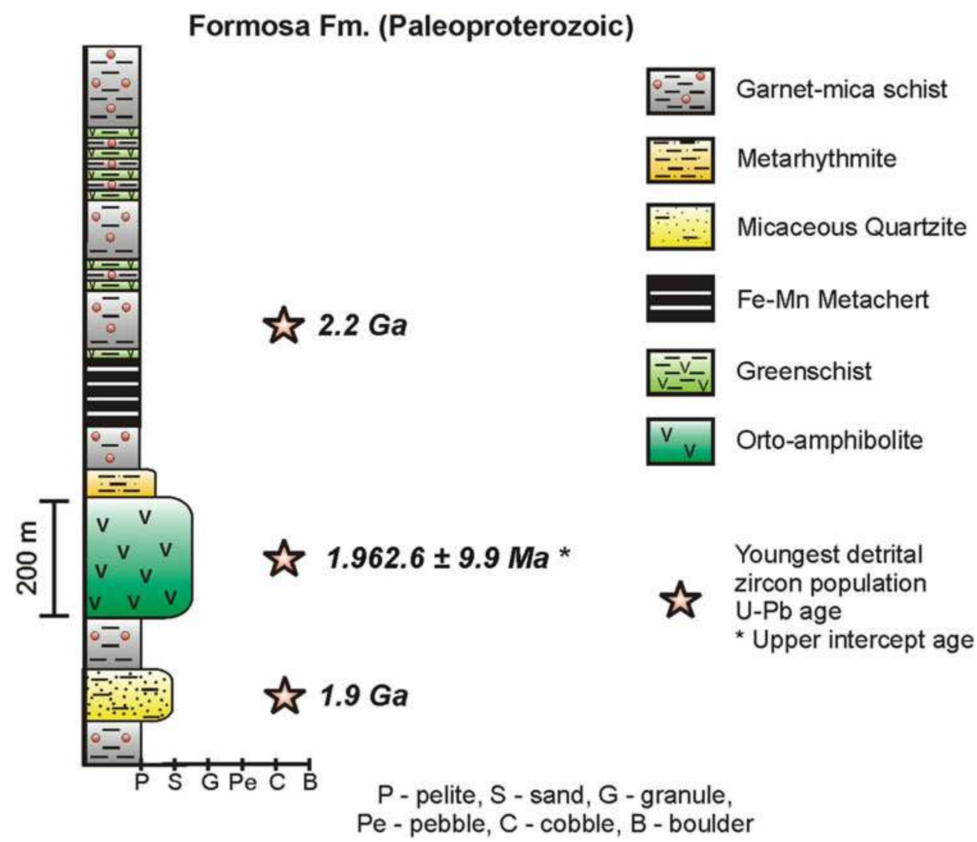


Fig. 12.3 Simplified transect of the Rio Preto fold belt and northwestern São Francisco craton. See Fig. 12.2 for location of the cross-section (modified from Egydio-Silva 1987; Egydio-Silva et al. 1989; Caxito 2010)

Fig. 12.4 Stratigraphic column of the Formosa Formation, Rio Preto belt (after Caxito et al. 2012a, 2014a)



12.2.1.2 Neoproterozoic Units

Canabravinha Formation

The Canabravinha Formation (Figs. 12.2 and 12.5) occurs in the southern portion of the Rio Preto belt, extending from the village of Cariparé towards north for almost 40 km. It is composed of texturally and mineralogically immature quartzites and metawackes (Fig. 12.6a), phyllite (locally carbonaceous), sand-pelite metarhythmite, metadiamictite (Fig. 12.6b), and, locally, metamarl (Fig. 12.5). The quartzites and metawackes show lithic, feldspathic, carbonate-rich and micaceous varieties. The conglomeratic varieties show graded (Fig. 12.6a), plane-parallel or cross-bedding, locally displaying climbing ripples. The vertical and lateral facies changes observed in the formation characterize a transition from coarse-grained rocks, on the south (metadiamictite,

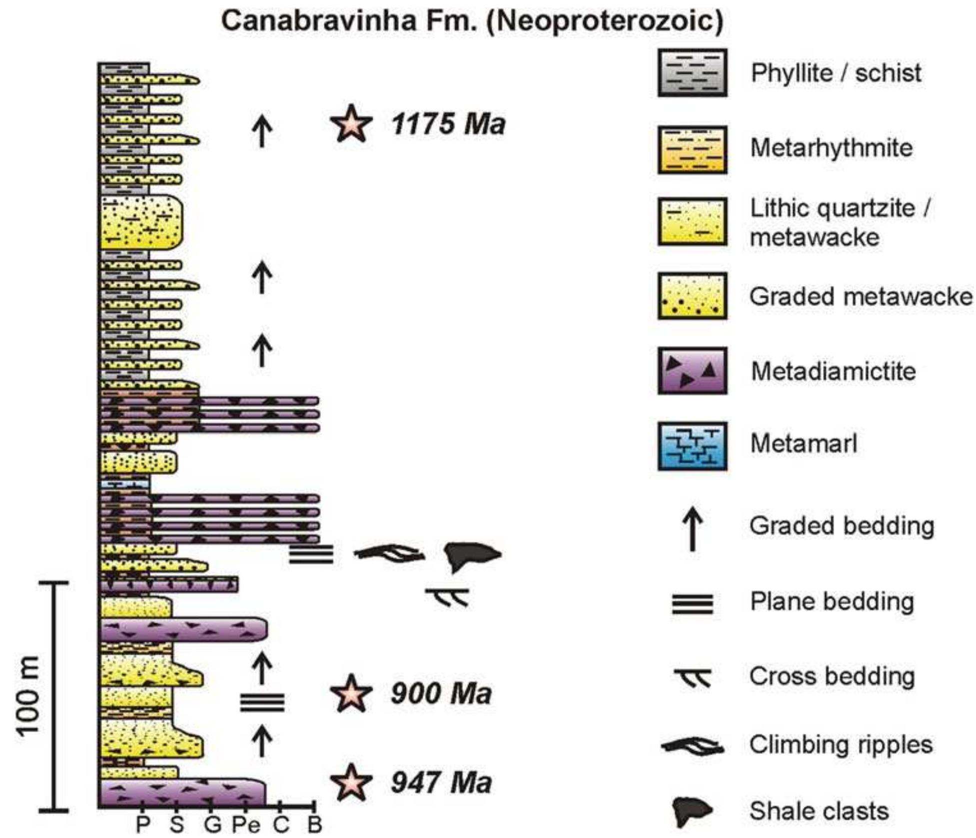


Fig. 12.5 Stratigraphic column of the Canabravinha Formation, Rio Preto belt (after Caxito et al. 2012a, 2014a)

metawackes), to medium and fine-grained facies, on the north (metarhytmite, phyllite). Caxito et al. (2012a) interpret the deposition of the Canabravinha Formation as occurring in a submarine gravel-rich slope-apron environment.

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. The Nd isotopes also indicate a larger variety of sources, with T_{DM} model ages between 1.5 and 2.7 Ga (Caxito 2010; Caxito et al. 2014a).

Caxito et al. (2012b) analyzed the isotopic composition of twelve carbonate clasts from the Canabravinha Formation, which yielded $\delta^{13}C$ values from −4.5 to 0 ‰, and $\delta^{18}O$ values of a more limited range, between −13.1 and −10.6 ‰. These results suggest erosion of a pre-glacial carbonate platform, for the fact that pre-glacial carbonate platforms are in general characterized by negative $\delta^{13}C$ anomalies, such as the Islay (~750 Ma) and Trezona (~635 Ma) anomalies documented worldwide (Halverson et al. 2010). No direct evidence for glacial influence on the deposition of the Canabravinha Formation such as dropstones and striated clasts were yet found. Likewise, a cap carbonate unit was never described in the Rio Preto fold belt. However, glacial periods favor the development of submarine slope-apron systems, as well as the associated lowering of the sea-level, causing exposure and erosion of the continental platform. Thus, the Canabravinha Formation could represent submarine gravitational re-sedimentation of glacially-related sediments.

The Canabravinha Formation is characterized by low to medium-grade metamorphism and complex structural evolution related to the Brasiliano orogeny, as indicated by K-Ar ages in muscovite around 590 Ma (Egydio-Silva 1987). The Canabravinha strata are thrust southward on top of the Serra da Mamona Formation of the Bambuí Group along the Cariparé shear zone and juxtaposed with the Formosa Formation by a reverse-dextral shear zone (Malhadinha-Rio Preto Shear Zone). Based on gravimetric data, Egydio-Silva (1987) estimates a thickness of almost 7500 m for the Canabravinha Formation. However, this estimation must be carefully interpreted, due to the high ductile deformation accommodated in these rocks, which are isoclinally folded in the central portion of the fold belt.

Bambuí Group

Egydio-Silva et al. (1989) subdivided the Bambuí Group in western Bahia state into three formations, including from the

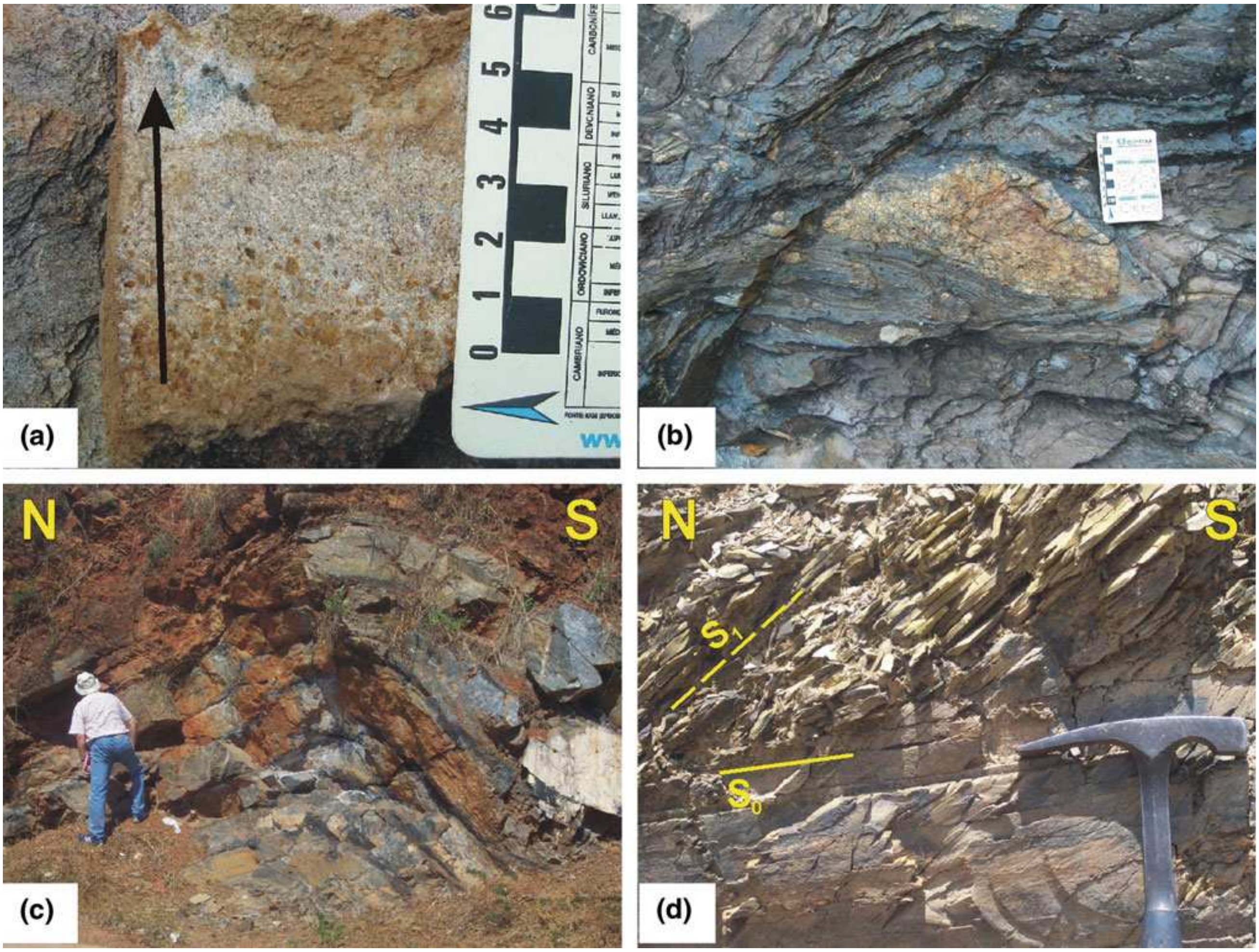


Fig. 12.6 **a** Graded bedding in coarse metagreywacke of the Canabravinha Formation, near Monte Alegre dos Cardosos, Bahia; **b** Granite boulder in metadiamictite of the Canabravinha Formation, Canabravinha creek; **c** Open fold with a E–W trending axis affecting limestones of the São Desidério Formation in the cratonic domain, São Desidério town, Bahia; **d** cross-cutting relationships between north-dipping bedding (S_0) and cleavage (S_1) in metapelite of the Serra da Mamona Formation, near Barreiras, Bahia

base to the top the São Desidério, Serra da Mamona and Riachão das Neves formations. Although this author considered the previously described Canabravinha Formation as the basal unit of the Bambuí Group, Caxito et al. (2012a) suggests that it should be better treated as a separate unit.

The São Desidério Formation is composed of dark gray limestones with intercalations of marls and siltstones, with an estimated thickness of 450 m (Egydio-Silva et al. 1989). The basal contact is not observed. The São Desidério carbonates are potential correlatives of the Sete Lagoas Formation that unconformably cover the basement gneisses in the intracratonic São Francisco basin (see Reis et al. 2017), as suggested by the upward increasing of $\delta^{13}C$ values exhibited by both units (Sial et al. 2010). The upper contact of the formation is characterized by a progressive increase in the proportion of clastic material in the carbonates, which grade into the metamarls and carbonatic slates of the Serra da Mamona Formation.

The Serra da Mamona Formation is marked by the intercalation of carbonate and pelite layers, affected by incipient to low grade metamorphism. Its thickness is estimated in 3000 m (Egydio-Silva et al. 1989), a value that must be carefully considered, for the intensively deformed unit.

On top of the Serra da Mamona Formation, the lithotypes of the Riachão dos Neves Formation show a gradual increase in grain size and a great amount of feldspar and lithic fragments, characterizing meta-arkoses and metagraywackes. This formation, with an estimated thickness of 4000 m, can be correlated to the Três Marias Formation (Egydio-Silva et al. 1989), exposed in the central São Francisco basin (see Reis et al. 2017).

12.2.2 Structure

In the northwestern Bahia state, S-N transect along route BR-135 between São Desidério and Cristalândia do Piauí highlights an example of the transition between the cratonic and the orogenic belt domains (Fig. 12.3). The undeformed flat laying Bambuí Group strata in the cratonic domain become progressively affected by flexural and concentric folds associated to an axial plane disjunctive cleavage in the pericratonic domain between the towns of Barreiras and Riachão das Neves (Fig. 12.6c). In the proximities of Cariparé, the folds become progressively tighter, becoming similar and isoclinal folds. In this region, the deformation history recorded by the Neoproterozoic rocks is quite complex and took place in three distinct phases (Egydio-Silva 1987; Caxito 2010; Caxito et al. 2014b).

The overall architecture of the Rio Preto belt is characterized by a double thrust wedge, in which the southern and wider portion displays a clear vergence towards 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 (Fig. 12.3) (Egydio-Silva 1987; Caxito et al. 2014b).

As demonstrated by the K-Ar age determinations carried out by Egydio-Silva (1987), the development of the Rio Preto belt probably results from a polyphase evolution related exclusively to the Brasiliano orogeny (600–540 Ma). The main deformational foliation recognized in the Rio Preto fold belt rocks (S_2) corresponds to the axial plane cleavage documented in the Bambuí Group exposed in the craton interior.

Only one deformational phase, marked by SSE-verging folds, can be recognized in the cratonic cover domain between the towns of Cariparé and São Desidério. An axial plane slate cleavage preferentially oriented at N60–70E/50°NW is associated with these folds (Fig. 12.6d), which exhibit nearly vertical short limbs and shallow plunges toward NE or SW. Reverse, south-verging faults can locally invert the stratigraphy within the cratonic cover. The folds become progressively symmetrical further south, but still showing a weak south-vergence near São Desidério (Fig. 12.6c). South of this town, the Bambui strata are undeformed and flat lying. The deformation in the cratonic domain is typically thin-skinned and associated with a regional detachment located along the basement-cover contact. Egydio-Silva (1987) estimates a shortening of about 15–20 % for this domain. The Cariparé shear zone, marking the boundary between the craton and the fold belt, is a NE-trending fault zone, along which the Canabravinha Formation are thrust towards SE on top of Serra da Mamona Formation.

Three main deformation phases can be recognized in the Rio Preto fold belt (Egydio-Silva 1987; Caxito 2010; Caxito et al. 2014b):

- Phase D_1 generated a penetrative S_1 foliation, which is in general parallel to the sedimentary bedding (S_0). The tectonic meaning of this phase is obscure due to intensive transposition in the subsequent phases.
- Phase D_2 is the main deformational phase, responsible for development of the double-verging large-scale structure of the belt. Gentle and concentric folds affecting the Bambuí Group in the external zone grade progressively into tight to isoclinal folds in the internal portions of the fold belt. This phase also generated the large ductile/brittle shear zones, among them the Cariparé and Malhadinha/Rio Preto faults (Fig. 12.3).
- Phase D_3 generated gentle to open folds associated with a south-dipping crenulation cleavage (S_3), generated in the course of a final hinterland-verging compression.

Caxito (2010) and Caxito et al. (2014c) proposed that the double thrust wedge that dominates the structural picture of the Rio Preto belt was produced by the oblique convergence between the São Francisco craton on the south and the Cristalândia do Piauí block on the north. 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 (Fig. 12.3).

12.3 The Transition Between the Rio Preto and Riacho do Pontal Belts

Sparse occurrences of supracrustal rocks (mainly mica schists) mark the transition zone between the Rio Preto and Riacho do Pontal belts located between the Boqueirão range and Campo Alegre de Lourdes town in Bahia state (Fig. 12.1). In this region, the supracrustal units are strongly deformed and cut by a system of curved, SSE-verging thrusts (Arcanjo and Braz Filho 1999) in a similar way as further south in the Irecê basin, where the Neoprotezoic cratonic cover was also transported southwards along a system of arcuated thrusts (Fig. 12.1) (Danderfer Filho et al. 1993; Arcanjo and Braz Filho 1999). The Boqueirão and Estreito ranges, underlain by quartzites of the Santo Onofre Group (Egydio-Silva 1987), might have acted as lateral ramps linked to the curved SSE-verging thrusts. The craton boundary exhibits a complex and irregular geometry in map-view in this region, which is not yet covered with detailed geological mapping.

12.4 The Riacho do Pontal Belt

The Riacho do Pontal fold belt (Brito Neves 1975; Caxito 2013) borders the São Francisco craton to the north in the states of Bahia, Pernambuco and Piauí (Figs. 12.1 and 12.7) and is bounded on the north by the western branch of the Pernambuco lineament, a continental-scale dextral strike-slip shear zone. On the eastern sector, the belt grades discontinuously into the Sergipano belt (Oliveira et al. 2017); on northwest sector, it is covered by the Phanerozoic strata of the Parnaíba basin (Fig. 12.1).

The original concept of the Riacho do Pontal as a Brasiliano orogenic belt was challenged in the eighties by some authors, who interpreted the deformation and metamorphism in the region as a manifestation of the Paleoproterozoic Transamazonian event (Jardim de Sá and Hackspacher 1980). The first Rb-Sr whole rock geochronological data of syn- to late-collisional plutons performed in the nineties yielded ages around 555 Ma (Jardim de Sá et al. 1992, 1996), confirming thus the original assumption by Brito-Neves (1975).

The Riacho do Pontal belt is subdivided in three sectors: the internal, central and external zones (Oliveira 1998; Caxito 2013; Caxito and Uhlein 2013; Caxito et al. 2016) (Fig. 12.8).

12.4.1 Stratigraphy

12.4.1.1 Basement

The basement of the belt in the Sobradinho dam area (Fig. 12.7) is represented by the Gavião/Sobradinho block of the São Francisco craton (Barbosa and Sabaté 2004; Dantas et al. 2010; Teixeira et al. 2017; Barbosa et al. 2017). TTG-orthogneisses with tonalitic, granodioritic and leucogranite bands predominate in the region. Supracrustal sequences, composed mainly of quartzite and calc-silicatic

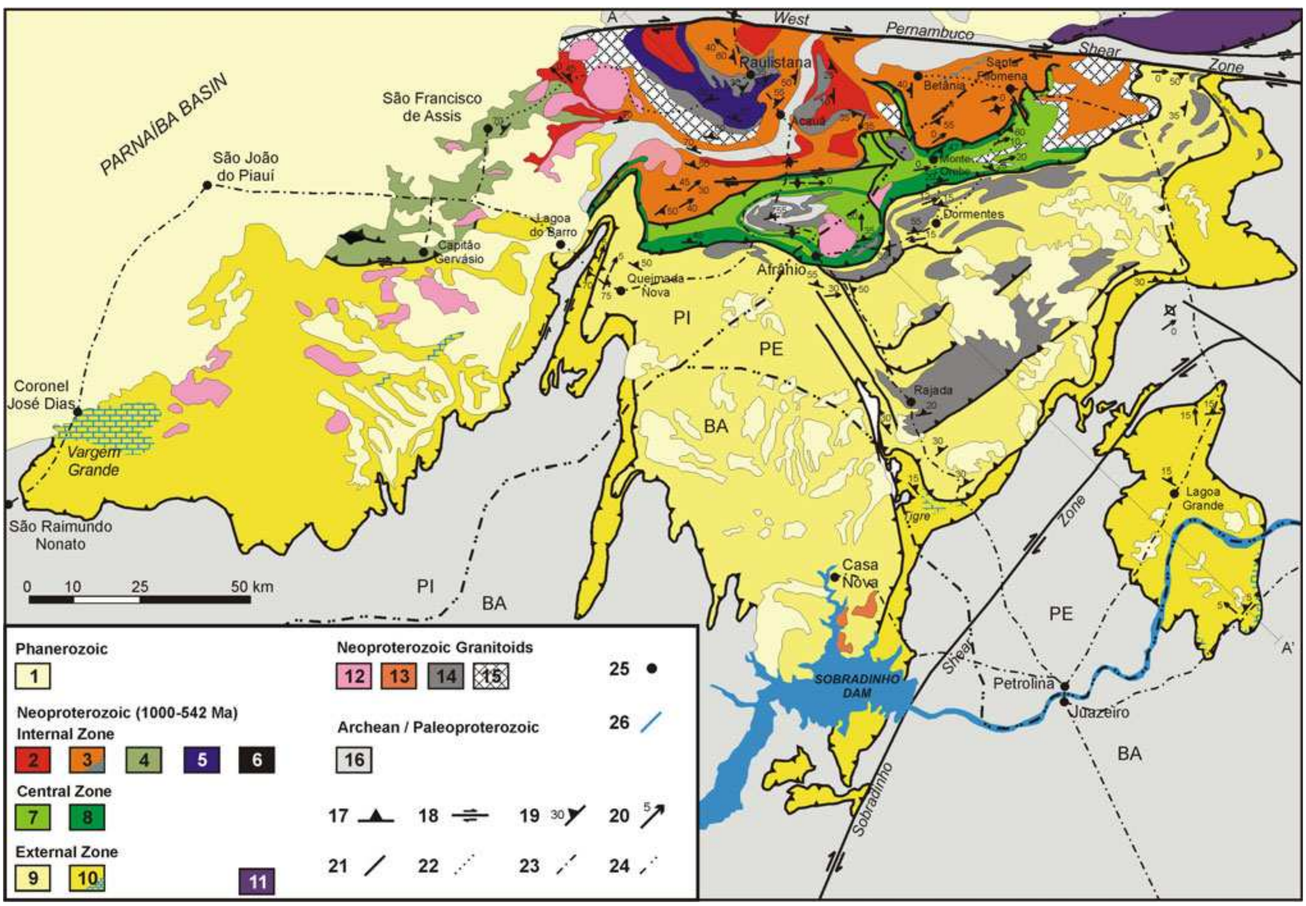


Fig. 12.7 Geologic map of the Riacho do Pontal fold belt (after Angelim and Kosin 2001 and Caxito 2013). *1*—Phanerozoic covers; *2*—Afeição Suite (1000–960 Ma); *3*—Santa Filomena Complex (brick pattern: marble); *4*—Morro Branco Complex; *5*—Paulistana Complex; *6*—Brejo Seco Complex; *7*—Monte Orebe Complex (metasedimentary rocks); *8*—Monte Orebe Complex (metavolcanic rocks); Casa Nova Group: *9*—Mandacaru Formation; *10*—Barra Bonita Formation (brick pattern: marble); *11*—Santana dos Garrotes Formation; *12*—Serra da Aldeia Suite; *13*—Serra da Esperança Suite (ca. 555 Ma); *14*—Rajada Suite (650-575 Ma); *15*—Undifferentiated granitoids; *16*—Archean/Paleoproterozoic basement; *17*—Thrust; *18*—Strike-slip shear zone; *19*—S_2 foliation; *20*—L_2 lineation; *21*—Interpreted photolineament; *22*—Land road; *23*—Paved road; *24*—Interstate border; *25*—City; *26*—São Francisco river

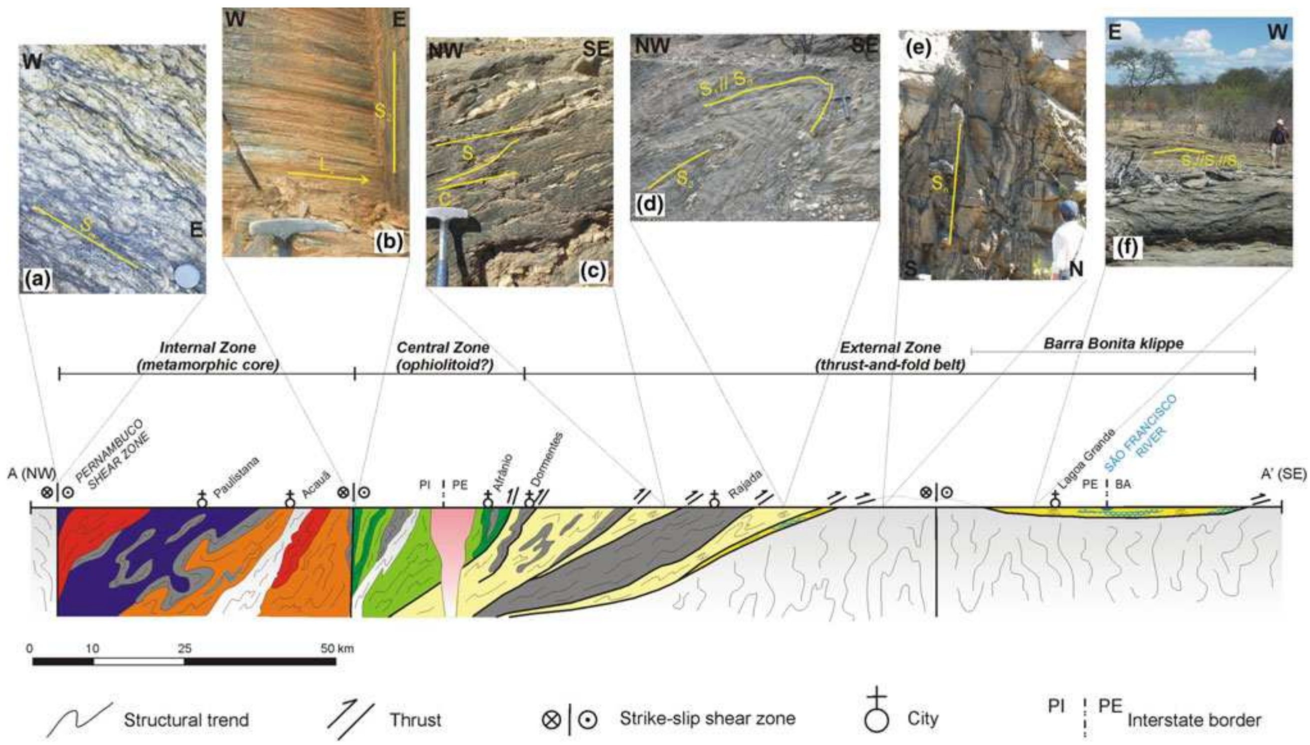


Fig. 12.8 Geologic transect of the Riacho do Pontal fold belt (Caxito 2013). Key is the same as in Fig. 7. **a** Mylonitic gneiss of the basement in the West Pernambuco shear zone; **b** greenschist of the Monte Orebe Complex, showing vertical foliation (S_2) and horizontal stretching lineation (Lx), near Afrânio, Pernambuco; **c** S-C structure in a schist of the Mandacaru Formation, indicating top-to-southeast motion; **d** tight F_2 fold affecting a schist of the Mandacaru Formation, near the basal thrust of the Casa Nova nappes, Pau Ferro town, Pernambuco; **e** vertical Sn (Paleoproterozoic?) banding in orthogneisses of the São Francisco basement, near Petrolina, Pernambuco; **f** horizontal $S_2//S_1//S_0$ foliation in schist of the Barra Bonita Formation within the Barra Bonita klippe, near Lagoa Grande, Pernambuco

rocks, as well as granitic plutons and amphibolite dykes are also locally important (Santos and Silva Filho 1990; Figueirôa and Silva Filho 1990). The available geochronological data suggests Archaean ages, with important Paleoproterozoic (2.2–2.0 Ga) orogenic reworking for these assemblages (Santos and Silva Filho 1990; Figueirôa and Silva Filho 1990; Barbosa and Dominguez 1996; Barbosa and Sabaté 2004; Dantas et al. 2010). Paleoarchean ages up to 3.5 Ga were recently found in gabbro-dioritic xenoliths in TTG rocks by Dantas et al. (2010), suggesting that some of the oldest rocks of South America are present in this region.

In the central portion of the belt, near the town of Afrânio in Pernambuco state, the basement crops out as tectonic slices interleaved within supracrustal rocks (Morro do Estreito Complex; Gava et al. 1983; Kosin et al. 2004).

12.4.1.2 Lithological Assemblages of the Internal Zone

The internal zone of the Riacho do Pontal belt (Figs. 12.7 and 12.8) involves volcanosedimentary sequences (Paulistana, Santa Filomena and Morro Branco complexes), intruded by large volume of igneous rocks, including the mafic-ultramafic complexes of Brejo Seco and São Francisco de Assis (Gomes and Vasconcelos 1991; Angelim and Kosin 2001; Caxito 2013; Caxito and Uhlein 2013; Gava et al. 1983; Angelim and Kosin 2001; Salgado et al. 2016), as well as the augen-gneisses of the Afeição Suite (Angelim 1988; Caxito et al. 2014c). These units are metamorphosed under upper greenschist to lower amphibolite facies conditions and intensively deformed.

The Paulistana Complex is composed of garnet-mica schists and muscovite quartzites with intercalations of greenschists (metabasalts) and amphibolites (metagabbros), containing ultramafic lenses. The metamafic rocks show high-Ti, high Th/Yb and Nb/Yb and are LREE- and LILE-enriched, similar to basalts extruded in present day evolved continental rifts or hyper-extended continental margins (e.g. the Red Sea rift margins). The U-Pb age of 882.8 ± 4.4 Ma constrains the age of crystallization of their magmatic protoliths (Caxito 2013; Caxito et al. 2016). Positive $\varepsilon Nd_{(882\ ma)}$ around +4.0 indicates involvement of a juvenile mantle source in their generation (Caxito 2013; Caxito et al. 2016).

The Santa Filomena Complex comprises coarse muscovite, biotite, garnet, kyanite, staurolite, cordierite and sillimanite schists, with local calcitic marble intercalations.

The Morro Branco Complex (Caxito 2013; Caxito and Uhlein 2013) consists of fine-grained quartz-mica schist and phyllite, metachert, quartzite, metabasalts, intermediate to acid metavolcanics, basic to felsic metatuffs, as well as subordinate graphite-schists. The intermediate to acid metavolcanics comprise rhyodacite, dacite, rhyolite and crystal tuffs. The metabasalts locally preserves amygdaloidal structures, suggesting eruption in a shallow, low-pressure environment. No geochronological data is available for the Morro Branco Complex.

Angelim and Kosin (2001) postulated that the above mentioned volcanosedimentary complexes are older than the intrusive 1000–960 Ma Afeição Augen Gneiss (Jardim de Sá et al. 1988, 1992; Van Schmus et al. 1995; Caxito et al. 2014c). Caxito et al. (2014c) presented a systematic petrographic, lithogeochemical, geochronological and isotopic study on the plutonic rocks of the Afeição Suite, suggesting that they represent the southwesternmost edge of the Tonian Cariris Velhos magmatic arc of the Transversal Zone of the adjacent Borborema Province (Kozuch 2003; Santos et al. 2010). U-Pb zircon ages of 1000–960 Ma, εNd(t) between −1.0 and +3.1 and T_{DM} model ages of 1.2–1.5 Ga corroborate this correlation (Van Schmus et al. 1995; Caxito et al. 2014c). However, at least the Paulistana Complex seems to be younger than the Afeição Suite, as indicated by the aforementioned U-Pb metagabbro age. The Morro Branco Complex and part of the Santa Filomena Complex might, on the other hand, be older than the Afeição Suite and probably representing volcanosedimentary sequences related to the Cariris Velhos event, a hypothesis that demands further tests.

The mafic-ultramafic Brejo Seco Complex is an approximately 10 km-long intrusion, tectonically interleaved within the Morro Branco volcanosedimentary sequence (Fig. 12.7). It is composed of a thin basal mafic unit (gabbros and troctolites), followed by variably serpentinized dunite, layered troctolite, minor olivine gabbro, layered gabbro, leucogabbro, minor anorthosite, ilmenite gabbro and ilmenite-magnetitite. The whole complex, with a maximum thickness of ca. 3 km, is tectonically inverted, with the ultramafic units (on the north) sitting on top of the mafic units (on the south). Basic dykes, represented by amygdaloidal diabase, crosscut the upper-layered gabbros. Both the northern and southern contacts are marked by EW-trending reverse shear zones. Preliminary geochemical data points to a tholeiitic geochemical affinity for the plutonic rocks of the Brejo Seco Complex, which was then suggested to be characteristic of island arc rocks (Marimon 1990). However, a systematical study on the petrogenetic and lithochemical evolution of the Brejo Seco Complex (Salgado 2014) suggests instead that it represents a classic mafic-ultramafic layered intrusion emplaced in a continental rift setting around 900 Ma ago (Salgado et al. 2016). A thick lateritic cover containing nickel deposits is developed above the ultramafic assemblage (Santos 1984). Approximately 40 km to the northeast of the Brejo Seco mafic-ultramafic exposures (Fig. 12.7), sparse outcrops of mafic and ultramafic rocks can be found. The region is highly weathered, and the rare outcrops that can be found are of coarse gabbro and serpentinite. If a correlation of the São Francisco de Assis and Brejo Seco complexes is admitted, then the zone of influence of mafic-ultramafic magmatism in the western portion of the Riacho do Pontal fold belt would extend up to 60 km in the NE–SW direction.

12.4.1.3 Lithological Assemblages of the Central Zone

The central zone of the Riacho do Pontal belt is characterized by a 100 km-long, EW-trending synformal structure, known as the Monte Orebe synform (Kreysing et al. 1973; Angelim 1988; Moraes 1992), which extends from the town of Afrânio, in the state of Pernambuco to Paulistana, in the state of Piauí (Figs. 12.7 and 12.8). Moreover, the central zone is characterized by a paired positive-negative linear Bouguer anomaly typical for suture zones (Gibb and Thomas 1976), which shows a difference of ca. 50 mgal from peak-to-peak (Oliveira 1998).

The dominant unit in the central zone, the Monte Orebe Complex, is made up mainly of basic metavolcanics (actinolite schists, amphibolites and metatuffs), interleaved within deep-sea pelagic metasedimentary rocks, mainly metachert (locally iron-rich) and garnet-mica schist, with local metagreywacke and quartz-schist. Locally, millimetric vesicular structures can be found in otherwise massive metabasalts (Fig. 12.9c). Medium to coarse grained ortho-amphibolites are also common and generally concordant to the actinolite-plagioclase greenschists.

Preliminary lithochemistry data of major and selected trace elements suggests a tholeiitic, MORB-type affiliation for the igneous protoliths of the Monte Orebe Complex (Moraes 1992). Caxito et al. (2014d) present new lithogeochemical and Sm–Nd isotope data on the metabasalts. Trace and rare earth elements data confirm a T-MORB chemistry, and Sm–Nd isotope data yields a whole-rock isochron age of 819 ± 120 Ma with an initial εNd(t) = +4.4, indicating derivation from a depleted mantle source. The Monte Orebe Complex might thus contain oceanic crust remnants, thereby marking a suture zone within the central portion of the belt (Caxito et al. 2014d, 2016).

12.4.1.4 Lithological Assemblages of the External Zone

The external zone of the Riacho do Pontal belt comprises the Casa Nova Group (Souza et al. 1979; Santos and Silva Filho 1990; Figueirôa and Silva Filho 1990; Bizzi et al. 2007) subdivided into two units: the Barra Bonita and Mandacaru formations.

The Barra Bonita Formation, composed mainly of fine-grained metapelitic rocks and muscovite quartzite (Fig. 12.9a) with marble lenses (Fig. 12.9b), is interpreted as

Fig. 12.9 **a** Muscovite quartzite of the Barra Bonita Formation, Ponta da Serra, Piauí; **b** folded marble of the Barra Bonita Formation, near Afrânio, Pernambuco; **c** amygdaloidal metabasalt of the Monte Orebe Complex, Serra do Trancelim, Dormentes—Santa Filomena road; **d** south-verging folds affecting the limestones of the Salitre Formation, Una basin, Chapada Diamantina region (photo by Daniel G.C. Fragoso, UFMG)

deposited in a shallow marine, platformal setting (Santos and Silva Filho 1990; Caxito 2013; Caxito et al. 2016). Fine to medium grained grey mica schists and phyllites predominate, with quartz, biotite, muscovite, garnet porfiroblasts, and minor detrital feldspar as the main mineral phases. The quartzites are commonly whitish and schistose, with muscovite and minor detrital feldspar. They occur mainly near the base of the Barra Bonita formation, in contact with the basement migmatites and gneisses. The marble lenses can reach thicknesses of up to 200 m, locally preserving original sedimentary structures (Fig. 12.7).

The Mandacaru Formation is composed mainly of garnet mica schists with centimetric intercalations of metagraywacke with detrital feldspar, quartz, muscovite, garnet and chlorite. Based on the composition and preliminary geochemical data, a deep-sea turbiditic, syn-orogenic sedimentation is inferred for the Mandacaru Formation (Santos and Silva Filho 1990).

Ongoing sedimentary provenance studies suggests that the Barra Bonita Formation represents the continuation of the northern São Francisco craton passive margin, with a detrital zircon age spectra of 1.6–2.1 Ga and T_{DM} values between 2.4 and 1.5 Ga (Caxito 2013; Caxito et al. 2016). These patterns are very similar to those of the Una Group of the Paramirim aulacogen (Chapada Diamantina region) (Santos et al. 2012), and might reflect sources of the São Francisco craton basement, along with the Proterozoic volcanosedimentary units of the Paramirim aulacogen. $\delta^{13}C$ data and $^{87}Sr/^{86}Sr$ around 0.7074–0.7080 for the marble intercalations within the Barra Bonita Formation (Caxito 2013; Caxito et al. 2016) are also very similar from those of the Salitre Formation of the Una Group (Misi and Veizer 1998), suggesting a broad Neoproterozoic carbonatic platform in this area.

The Mandacaru Formation, on the other hand, presents quite distinct provenance patterns, with T_{DM} model ages around 1.6–1.4 Ga (Van Schmus et al. 2011; Caxito 2013; Caxito et al. 2016). U-Pb detrital zircon data for the Mandacaru Formation and for the upper portion of the Monte Orebe Complex indicates a peak at 1.0 Ga, with the youngest detrital zircons around 640–665 Ma (Caxito 2013; Brito Neves et al. 2015; Caxito et al. 2016). These data suggests assemblages of the internal zone of the belt, including the Afeição Suite augen-gneisses and Stage I Brasiliano granites of the Borborema Province (Van Schmus et al. 2011), as source for these units. Thus, an important shift in sedimentary provenance is marked by the transition from the Barra Bonita Formation (passive margin with provenance from the craton) into the Mandacaru Formation (syn-orogenic sedimentation with provenance from the internal zone (Caxito 2013; Caxito et al. 2016).

12.4.1.5 Neoproterozoic Granitoids

The Riacho do Pontal belt contains a large number of Neoproterozoic granitoid plutons emplaced from the syn- to the post-collisional development stages (Fig. 12.7).

The syn-collisional magmatism is represented by tabular bodies of mesocratic, fine to medium-grained two-mica orthogneisses (Rajada Suite; Siqueira Filho 1967; Santos and Caldasso 1978; Gomes and Vasconcelos 1991). Based on the geochemical characteristics of the Rajada Suite syn-collisional orthogneisses, Angelim (1988) suggested that they generated by melting of the Casa Nova metagreywackes, due to the heating produced by crustal thickening during the main deformation phase recorded in the belt. Preliminary U-Pb zircon data indicates crystallization ages between 620 and 575 Ma (Caxito 2013; Brito Neves et al. 2015; Caxito et al. 2016).

The Serra da Esperança Suite represents the syn- to late-collisional magmatism, and comprises grey to pinkish syenites, quartz-syenites and associated granites, as well as pegmatite and syeno-granite dykes, which intrudes the Casa Nova metasedimentary rocks in the Sobradinho Dam area (Pla Cid et al. 2000) (Fig. 12.7). A Rb-Sr whole-rock isochron age of 555 ± 10 Ma (Ri = 0.7068 ± 1) reported by Jardim de Sá et al. (1996) is the best available estimation for emplacement and deformation of the Serra da Esperança Suite.

The last expression of magmatic activity in the Riacho do Pontal belt is represented by the late- to post-collisional Serra da Aldeia/Caboclo Suite. This unit occurs as circular to oval plutons, concentrated in the northwestern part of the belt (Gava et al. 1984). It is composed of grey to pink medium to coarse-grained syenite and K-feldspar granite, locally affected by late-stage shear zones. A limited number of chemical analyses performed in this unit indicates an alkaline affinity, with peralkaline/shoshonitic/potassic terms (Gava et al. 1984; Pla Cid et al. 2000).

12.4.2 Structure

The Brasiliano deformation took place in two main phases in the Riacho do Pontal belt: the contractional D_n and the strike-slip D_{n+1} phases (Gomes 1990; Gomes and Vasconcelos 1991; Caxito 2013; Caxito and Uhlein 2013).

The D_n phase corresponds to a progressive regional deformation, assisted by magmatism and metamorphism, during which a system of nappes were transported southwards along low-angle detachment surfaces. The frontal thrust zone of this system is marked by blastomylonites exhibiting a variety of kinematic indicators (Fig. 12.8c). The D_n phase led to the nucleation of three generations of folds and associated axial plane foliations. The most prominent among them is the S_2 foliation associated with the dominant south-verging tight to isoclinal F_2 folds (Fig. 12.8d) coeval to the Casa Nova nappes. A down-dip stretching lineation, plunging between NW and NNW, is normally associated with the S_2 foliation.

The metamorphism associated D_n phase reaches the amphibolite facies conditions and generated the Rajada Suite syn-collisional intrusions through crustal melts. The metamorphic isogrades show a inverse pattern within the nappes, the upper structures showing higher grade parageneses.

The manifestations of the second D_{n+1} phase are dextral strike-slip motions accommodated along EW-trending shear zones. The West Pernambuco shear zone is the master structure related to the D_{n+1} phase (Figs. 12.1 and 12.7). This continental scale shear zone is associated with a high-grade mylonitic foliation that overprints all units of the internal zone of the belt. Away from the Pernambuco shear zone, the D_{n+1} deformation is represented by a train of open folds, whose axial plane is marked by a crenulation cleavage (Fig. 12.7).

A number of subsidiary EW-trending sub-vertical shear zones related to this phase can be observed along the road connecting the towns Afrânio and Paulistana. These structures transpose preexistent contractional fabric elements, generating a penetrative sub-vertical mylonitic foliation with an associated E–W oriented stretching lineation (Fig. 12.8b). Syn-kinematic garnet porphyrclasts attests the overall dextral sense of shear along these structures.

Vauchez and Egydio-Silva (1992) estimated the P-T conditions for the development of the West Pernambuco shear zone at around 630–700° C and 6 kbar, which are consistent with syn-kinematic partial melting of the units involved. Towards east, the West Pernambuco shear zone terminates in form of a horsetail structure, which resolves the strike-slip deformation in a wide transpressional zone (Vauchez and Egydio-Silva 1992).

12.4.2.1 Effects of the Riacho do Pontal Deformation Within the Northern São Francisco Craton

Near the Sobradinho Dam area (external zone), a large number of isolated schist outcrops characterize klippen structures (Figs. 12.7 and 12.8f), which testify the original extension of the Neoproterozoic nappes. The basement outcrops between the Casa Nova nappe front and these klippen commonly show no sign of Brasiliano deformation, preserving the original Paleoproterozoic NS-trending vertical foliation characteristic of the Eastern Bahia orogenic domain (Barbosa and Barbosa 2017) (Fig. 12.8e). In contrast to the central and internal zones, the external domain corresponds to a thin-skinned deformation front, which propagates even further south, affecting the cratonic cover within the northern Paramirim aulacogen (see Cruz and Alkmim 2017). The contraction D_n deformation evolved, thus, from a thick-skinned domain on the north, to a thin-skinned zone on south, in which tectonic displacements are in the order of 30–60 km, as estimated by Jardim de Sá et al. (1992).

Proterozoic cover units of northern Paramirim aulacogen in the Chapada Diamantina region are affected by S-verging thrusts and folds that represent a manifestation of the Brasiliano thin-skinned deformation front 250 km south of the craton boundary (Figs. 12.1 and 12.9d) (Danderfer et al. 1993; Cruz and Alkmim 2017).

12.5 A Tectonic Model for the Northern São Francisco Craton Margin Belts

During the early Neoproterozoic (~900–820 Ma), the northern sector of the São Francisco paleocontinent was the site of intense crustal stretching, which led to the development of rift to passive margin basins. The widespread occurrence of mafic dyke swarms in the craton interior (Girardi et al. 2017) marks this extensional period. The emplacement of mantle plumes beneath the future cratonic margins might have been one of the causes for crustal warping and stretching. One of these plumes was probably located in the northern São Francisco craton margin and responsible for the emplacement of mafic-ultramafic complexes such as the Brejo Seco and São Francisco de Assis involved in the Riacho do Pontal belt (Salgado et al. 2016; Caxito et al. 2016). The Paulistana Complex, extruded in a continental rift environment at around 882 Ma (Caxito et al. 2016), also marks this phase of crustal stretching. The positive $\varepsilon Nd_{(882\ ma)}$ values around +4.0 suggests the involvement of large portions of a juvenile mantle source, such as in mantle upwelling areas, in the transition of active-type continental rifts to passive margins (Caxito 2013).

The development of the Rio Preto basin is probably related to this rifting event, which might extend throughout the Santo Onofre basin of the São Francisco craton and towards the Macaúbas basin of the Araçuaí Orogen further east (Fig. 12.10; Schobbenhaus 1996; Alkmim et al. 2017). The Canabravinha Formation was then deposited in a hemi-graben basin located within the Archean/Paleoproterozoic basement of the region (Fig. 12.10).

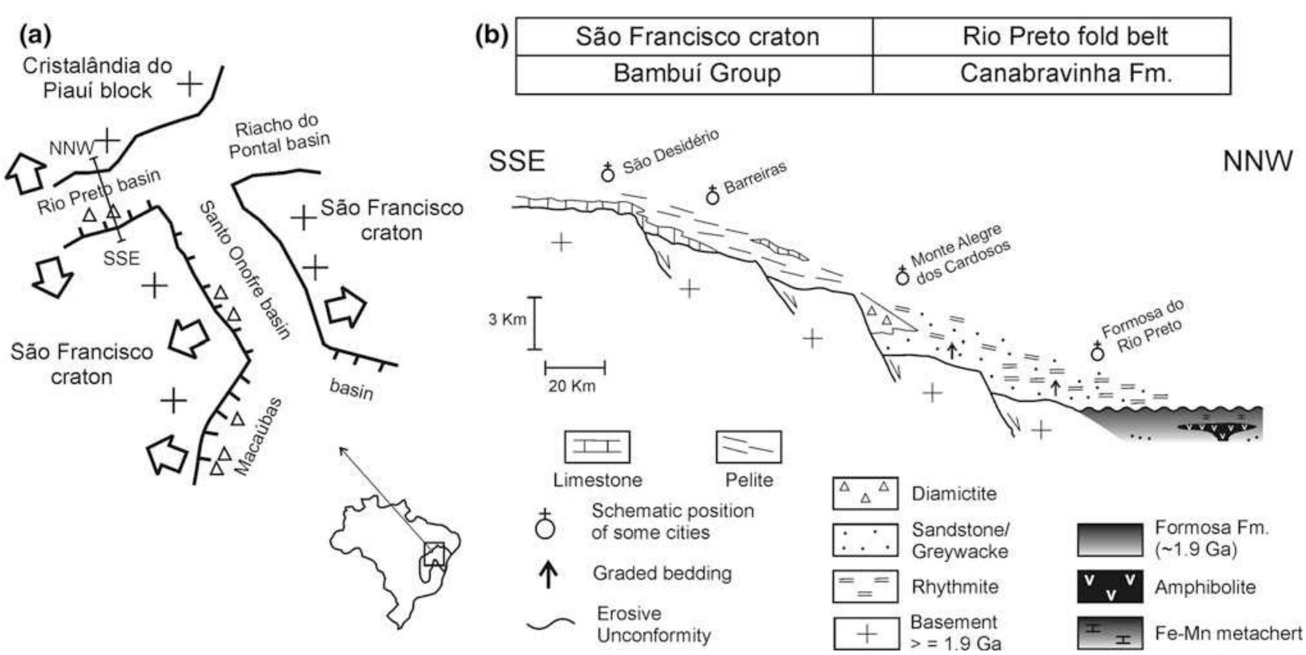


Fig. 12.10 Paleogeographic model for the Rio Preto area. See text for explanation (from Caxito et al. 2012a)

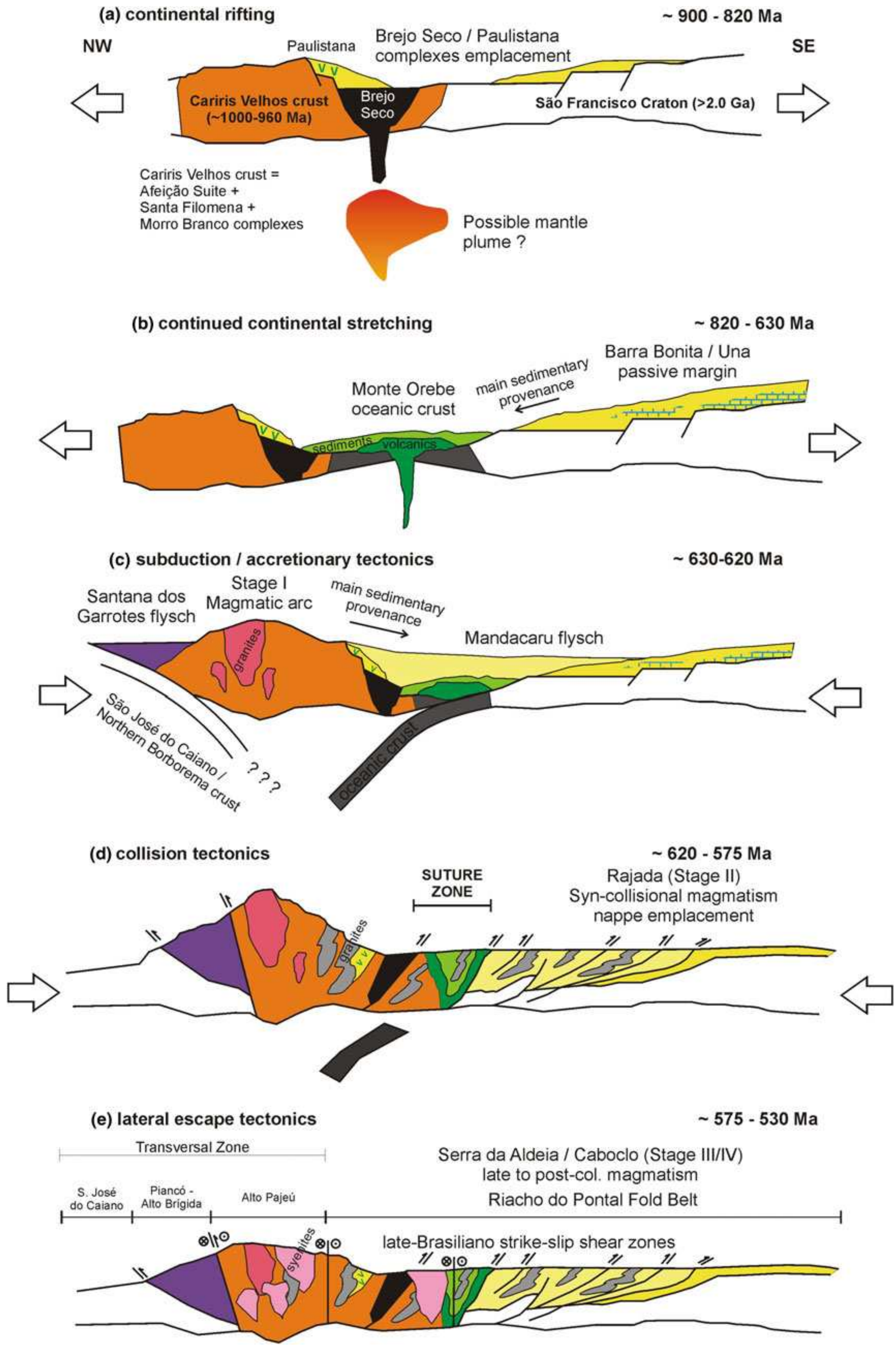


Fig. 12.11 Paleogeographic and tectonic model for the Riacho do Pontal belt. See text for discussion (from Caxito 2013; Caxito et al. 2016)

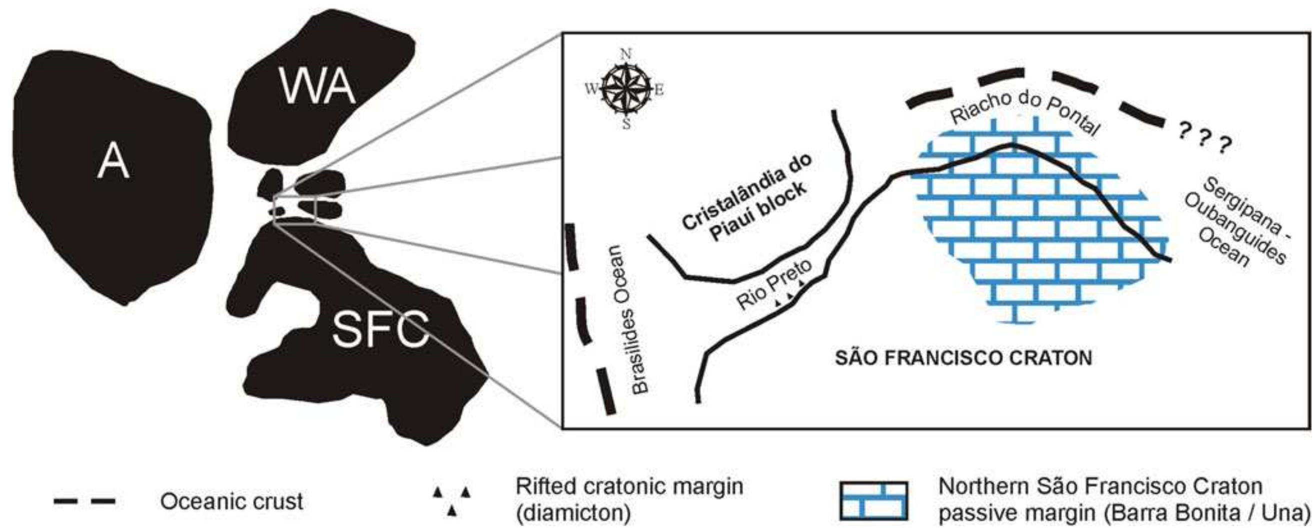


Fig. 12.12 Paleogeography of the northern São Francisco Craton margin and adjoining areas during the Late Neoproterozoic (ca. 650–630 Ma). *A* Amazon, *WA* West Africa, *SFC* São Francisco-Congo (modified from Caxito 2013)

Between 820 and 630 Ma, with progressive stretching of the continental crust, passive margins started to fringe the São Francisco continent on all sides. The Barra Bonita Formation of the Riacho do Pontal fold belt represents a typical platformal unit, which might be correlated to similar units within the cratonic area (e.g. the Salitre Formation of the Una Group). A tectonic model for the São Francisco northern margin during the Neoproterozoic would involve a broad passive margin represented by the Una Group carbonate platform and the Barra Bonita platformal quartzites with marble intercalations (Fig. 12.11a, b). Further north, the Monte Orebe Complex metabasalts seem to represent relicts of a Neoproterozoic oceanic crust coupled the passive margin (Caxito 2013; Caxito et al. 2016).

The rift and passive margin basins were inverted during the Brasiliano orogeny (630–530 Ma), which involved intense magmatism, metamorphism and deformation in the Riacho do Pontal belt area (Fig. 12.11c–e). Syn-orogenic sedimentation is represented by the Mandacaru Formation (Fig. 12.11c). The Riacho do Pontal belt probably represents a collisional orogen originated by the subduction of the São Francisco paleoplate towards north, below the western edge of the Pernambuco-Alagoas block of the Borborema Province, with consumption of the Monte Orebe oceanic crust (Fig. 12.11c, d). Finally, an important phase of lateral escape at ca. 575–530 Ma followed the continental collision leading to the development of crustal scale structures, such as the West Pernambuco shear zone, as well as granite and syenite intrusions of the Serra da Aldeia and Caboclo Suites (Fig. 12.11e).

The lack of evidence for oceanic crust and a Brasiliano subduction zone suggests an ensialic evolution for the Rio Preto belt, which seem to represent a strongly inverted rift basin. Stresses generated in the surrounding Tocantins and Borborema provinces could have been the cause of the inversion (Fig. 12.10).

In sum, the northern São Francisco craton margin evolved from an initial stage of crustal stretching and rifting in the early Neoproterozoic ($\sim$900–820 Ma) to a stage of passive margin development during the Cryogenian-Ediacaran ($\sim$820–635 Ma). While the Riacho do Pontal fold belt records the development of a full passive margin, including probable oceanic crust remnants (Caxito et al. 2014d), the Rio Preto fold belt might represent a failed rift arm, or aulacogen (Fig. 12.12). Altogether, the Rio Preto, Riacho do Pontal and Sergipano fold belts represents a continental scale orogenic system that extends over 1000 km along northern São Francisco craton margin.

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