Nature and Evolution of the Archean Crust of the São Francisco Craton

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3 Nature and Evolution of the Archean Crust of the São Francisco Craton

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Abstract

We overview the Archean tectonic framework the São Francisco craton based on geologic constraints, integrated geochronologic interpretation and isotopic-geochemical evidence of basement rocks. U–Pb provenance studies of Archean and Paleoproterozoic supracrustal sequences are also used to provide additional inferences about the geodynamic scenario. The Archean rocks crop out mainly in two large areas in the southern and northern portions of the craton, surrounded and/or in tectonic contact with Paleoproterozoic orogenic belts. The ancient substratum is essentially composed of medium- to high-grade gneissic-migmatitic rocks including TTG suites and coeval granite-greenstone associations that collectively provide an isotopic record as old as 4.1 Ga. The combined U–Pb and Sm–Nd T_{DM} age peaks coupled with U–Pb inherited ages in detrital zircons from the supracrustal sequences indicate that very ancient continental crust (>3.5 Ga) exist, particularly in the northern portion of the craton. Mesoarchean events are episodic between 3.6–3.3 and 3.2–2.9 Ga, as for the Neoarchean (2.8–2.6 Ga) in both cratonic portions. This isotopic record indicates a protracted Archean history for the São Francisco craton, highlighted by peculiar tectonic-metamorphic histories of the basement rocks. From a tectonic point of view the compiled data concur with a diachronic evolution from Paleo- to Neoarchean times by means of juvenile accretion/differentiation events characterized by multiple TTG plutonism in genetic association with greenstone belts, coupled with partial melting events of earlier-formed material. All ancient basement complexes and/or continental blocks assembled diachronically during the Late Neoarchean by convergence-related processes akin to plate dynamics. Late-tectonic K-rich granitoids, mafic-ultramafic complexes and mafic dikes collectively mark the Neoarchean thickening and final cratonization of the continental crust.

Keywords

Archean • TTG crust • Greenstone belts • K-rich granitoids

3.1 Introduction

The São Francisco craton (SFC) offers an ideal scenario to study aspects of the Archean geology, leading to the understanding of the early geodynamics of Earth, when significant portions of the continental crust formed and stabilized. The oldest components so far detected in the craton include tonalite-trondhjemite-granodiorite (TTG) rocks and

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granite-greenstone associations along with high-grade rocks, all of them providing an isotopic record that extends from ca. 4.1 to 2.5 Ga.

In this chapter, we overview the geologic-tectonic framework of the Archean basement based on the integrated interpretation of U–Pb ages for gneissic and granitic rocks in conjunction with detrital zircon geochronology of the Archean and Paleoproterozoic supracrustal sequences of SFC. An integrated interpretation of U–Pb ages and isotope data with major and trace element geochemistry from Archean igneous rocks provides additional clues about the geodynamic evolution. However, we are aware that this knowledge is limited, owing to the lack of preservation of the ancient crust and/or reworking by successive orogenic events (Cordani et al., this volume). The text follows the classical systematization of Archean basement complexes (e.g., gneissic-granitic, granite-greenstone, high-grade terrains) and Archean/blocks/fragments to address the most relevant components of the crystalline basement in the southern and northern portions of the SFC in extent and ages (Fig. 3.1). As a whole, our tectonic interpretation was based on the evaluation of published and new isotopic and geochemical data, as follows: (i) U–Pb ages on zircons (SHRIMP, TIMS, LA-ICP-MS) are considered as recording the timing of the major accretionary episodes; (ii) U–Pb ages of detrital zircons (supracrustal sequences) are also merged to infer the ages of the Archean sources and related crust-formation episodes; (iii) depleted mantle Sm–Nd model ages (T_{DM}) and their coherence with U–Pb dating are used for inferences about the time of mantle/differentiation episodes; (iv) $\varepsilon_{Nd(t)}$ and $\varepsilon_{Hf(t)}$ isotopic constraints are used for identifying the major petrogenetic components of a given magmatic event, whether juvenile or reworked ones; (v) geochemical data (e.g., REE) of igneous and metaigneous rocks are combined with the bulk isotopic signature of a given block or regional metamorphic complex to evaluate the nature of the accretion events and to infer the likely tectonic setting.

3.2 The Archean Record of the São Francisco Craton

The Archean basement assemblages crop out in the southern and northern lobes of the craton. Smaller exposures include a fault bounded block in the central portion of the Paramirim aulacogen in the northern portion of the craton, and stratigraphic windows in the interior and margins of the São Francisco basin (see Reis et al.; Cruz and Alkmim, in this book) (Fig. 3.1b, c). Different approaches, and consequently, different subdivision criteria have been used by authors working in the Archean terrains of the southern and northern cratonic portions. The southern exposure encompasses the Quadrilátero Ferrífero mining district (see Alkmim and Teixeira, this book) and adjoining areas, where the Archean substratum has been traditionally subdivided into various metamorphic complexes and greenstone belts (e.g., Rio das Velhas Supergroup), largely overprinted by Paleoproterozoic episodes. The Archean assemblages exposed in the northern portion comprise, on the other hand, a mosaic of individual Archean blocks bounded by the Paleoproterozoic orogenic domain of eastern Bahia (see Barbosa and Barbosa, this book). Correlations between the southern and northern portions regarding the Archean evolution are yet imprecise, which led us to present separated descriptions for them.

The Archean/Paleoproterozoic basement of the SFC is an extension of the much larger Congo craton of western-central Africa (e.g., Trompette 1994) (Fig. 3.1a). It consists of distinct Archean blocks, dated between 3.5 and 2.5 Ga. They are composed of polyphase medium- to high-grade metamorphic rocks and granite-greenstone associations (e.g., Chaillu-Gabon, Angola, Kasai, Uganda, Tanzania, E-Zaire) intruded in places by granitoid rocks, gabbro-anorthosite complexes and mafic dikes. In a similar way as the SFC, these blocks were extensively affected by Paleoproterozoic orogenic episodes (the Eburnean orogeny; 2.3–1.9 Ga), during which amalgamation of the proto-West Congo craton occurred (Cahen et al. 1984; Teixeira and Figueiredo 1991; Borg and Shackleton 1997; Ernst et al. 2013). In particular, Iizuka et al. (2010) used U–Pb dating of detrital zircons from the Congo river sands to evaluate the relevant age peaks in relation with the timing of supercontinent assembly. Coupled Hf isotopic constraints provided a further clue for the nature of the crustal components that participated in the sedimentary system through time. For instance, the slightly positive to moderately negative $\varepsilon_{Hf(t)}$ values suggest that episodes of crustal derived granitoid magmatism (Hf T_{DM} ages in the range of 3.3–3.0 and 2.9–2.6 Ga) have been the primary agent of differentiation of the continental crust (plus sedimentary recycling) since the Archean Eon. As such, this evolutionary history is analogous to that of the SFC as presented below.

3.3 Archean Assemblages of the Southern Portion of the Craton

Distinct Archean gneissic-granitic complexes characterize the southern portion of the SFC (e.g., Campo Belo, Santa Bárbara, Belo Horizonte, Bonfim, and Passa Tempo) (Fig. 3.2). They constitute a medium- to high-grade metamorphic terrain that crops out from the Quadrilátero Ferrífero towards the west, and mainly comprises TTG rocks, migmatites and K-rich granitic plutons. Remnants of supracrustal rocks, as well as mafic-ultramafic layered bodies and mafic dikes are also present (e.g., Machado et al.

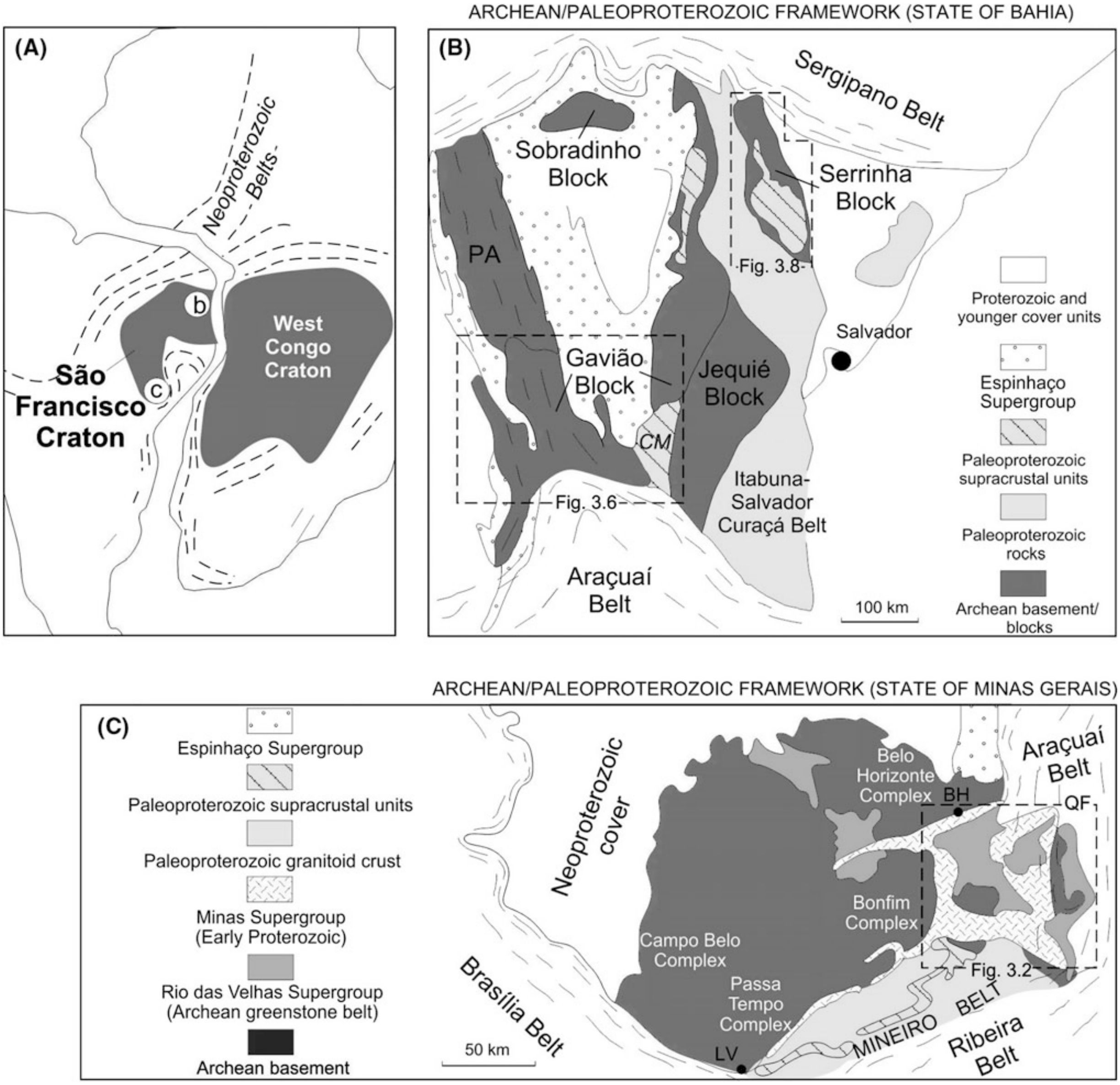

Fig. 3.1 **A** Tectonic sketch of the São Francisco craton and the adjoining West Congo craton, outlined by the Neoproterozoic marginal belts. *Insets* **B** and **C** show the geologic framework on the northern and southern portions of the craton, emphasizing the extent of the Archean basement and the adjoining Paleoproterozoic belts. Keys (**b**): *PA* Paramirim aulacogen, *CM* Contendas-Mirante supracrustal belt. See text for details

1992; Teixeira et al. 2000; Pinese et al. 1995; Alkmim and Noce 2006; Romano et al. 2013; Lana et al. 2013; Goulart et al. 2013). These metamorphic complexes show contrasting orientations of both mylonitic foliation and transpressional structures, and record three deformational and metamorphic Archean episodes, namely the Rio das Velhas I, II, III events (see Table 3.1 in Campos and Carneiro 2008 and references therein).

Notably, Lana et al. (2013) who investigated the polydeformed TTG rocks in the Quadrilátero Ferrífero by means of detailed U–Pb geochronology deciphered an episodic accretion of the crust in the time intervals of 3.21–3.10, 2.93–2.90, and 2.80–2.77 Ga. The youngest episode includes widespread K-rich plutonism, recently reassessed by Romano et al. (2013) based on extensive zircon U–Pb work and previously published information. The Neoarchean

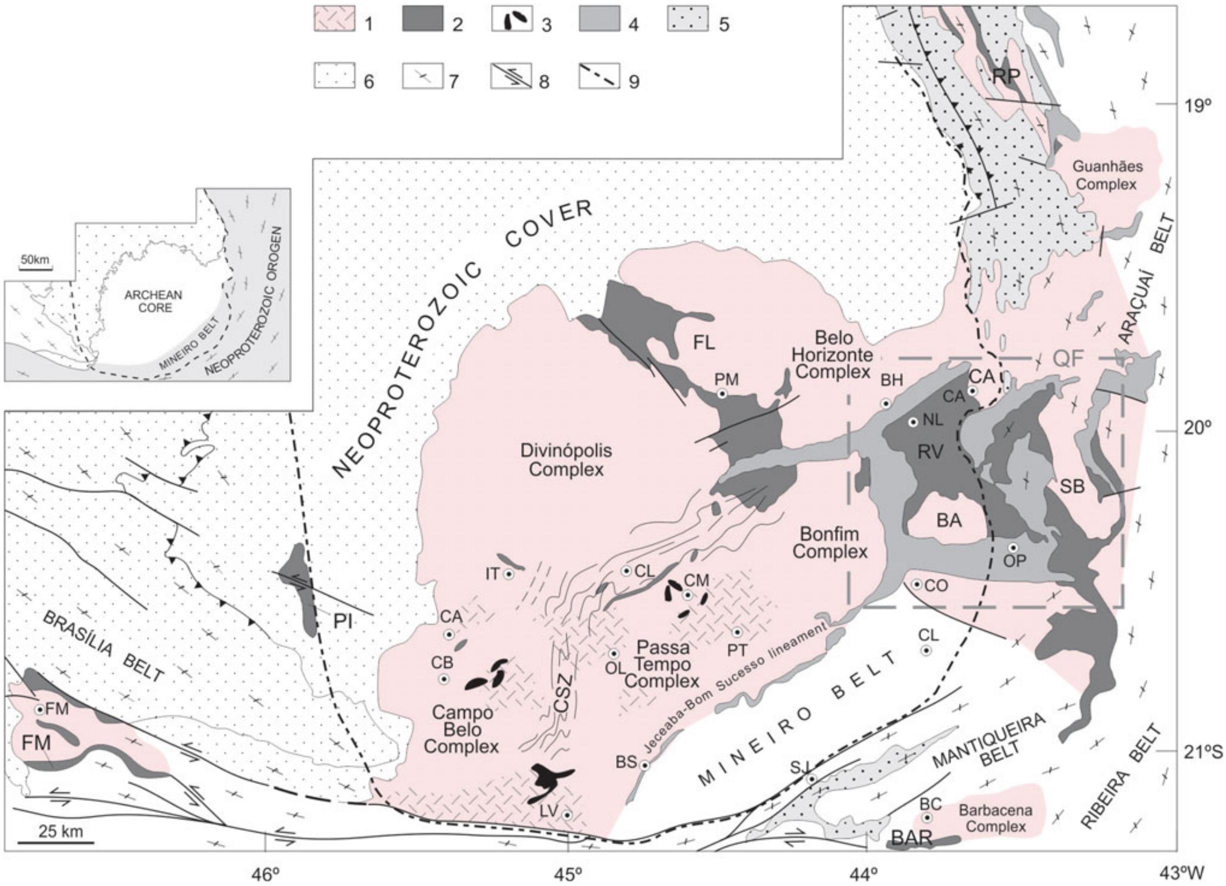

Fig. 3.2 Geologic sketch of the southern segment of the SFC showing the Archean landmass, distinguished by the Campo Belo, Passa Tempo, Bonfim and Belo Horizonte metamorphic complexes, as well as by gneissic-migmatitic domes: SB (Santa Bárbara), CA (Caeté), FL (Florestal), BA (Bação). The Paleoproterozoic Mineiro and Mantiqueira belts and scattered Archean sialic remnants (Barbacena, Guanhães, Gouveia) within the Neoproterozoic marginal belts are also shown (adapted from Noce et al. 2007a, b; Seixas et al. 2012; Lana et al. 2013). *1* Archean crust; *2* Archean greenstone belts: RV (Rio das Velhas Supergroup), RP (Rio Paraúna), PI (Piumhi), FM (Fortaleza de Minas), BAR (Barbacena), *3* Mafic-ultramafic complexes. *4* Minas Supergroup, *5* Espinhaço Supergroup, *6* Bambuí Group, *7* Neoproterozoic reworking/overprint, *8* faults, *9* limit of the SFC. Keys: CSZ = Cláudio shear zone. Towns: FM (Fortaleza de Minas), CB (Campo Belo), CA (Candeias), IT (Itapecerica), CL (Cláudio), CM (Carmópolis de Minas), OL (Oliveira), PT (Passa Tempo), LV (Lavras), BS (Bom Sucesso), PM (Pará de Minas), NL (Nova Lima), CA (Caeté), OP (Ouro Preto), CO (Congonhas), CL (Conselheiro Lafaiete), SJ (São João del Rei), BC (Barbacena). See text for details

magmatic event, regionally dated between 2.79 and 2.70 Ga by several authors in the southern SFC, has been traditionally attributed to the so-called Rio das Velhas orogeny, during which the Rio das Velhas greenstone belt and coeval gneissic-granitic complexes were formed in an active continental margin setting (e.g., Noce et al. 2005, 2007b; Machado and Carneiro 1992). Subordinate calc-alkaline and tholeiitic magmatism has been ascribed to the syn- to late orogenic stages (e.g., Engler et al. 2002; Goulart et al. 2013). A regional NE–SW trending shear zone (Claudio Shear Zone) transects the central portion of the ancient substratum as evidenced by aeromagnetic data. Along this shear zone the country rocks show dextral kinematics and mylonitic character (Oliveira and Carneiro 2001; Campos et al. 2003; Campos and Carneiro 2008) (Fig. 3.2).

A precursor Paleoarchean continental crust can be envisaged by few isotopic data from basement and supracrustal rocks of the southern SFC. The evidences are: (i) subordinate distribution of whole rock Sm–Nd T_{DM} ages in orthogneisses varying from 3.5 to 3.3 Ga (Carneiro et al. 1998; Teixeira et al. 2010; W. Teixeira, unpublished data); (ii) inherited zircon population dated at 3374 Ma (concordant $^{207}Pb/^{206}Pb$ age) from the Neoarchean Carmópolis de Minas mafic-ultramafic suite (see Goulart et al. 2013); (iii) U–Pb ages of detrital zircons from Archean (Rio das Velhas Supergroup) and Paleoproterozoic metasedimentary

Table 3.1 Characteristics of the Archean evolution of the southern SFC based on new data and compiled information

Events	U–Pb age range (Ga)	Geologic-tectonic characteristics	Isotopic constraints
Neoarchean/Early proterozoic	–	Crustal exhumation and tectonic stability of the continental mass	–
Neoarchean 2: Rio das Velhas orogeny (late episode)	2.72–2.70$^{(ca)}$ 2.61–2.55$^{(gp)}$	Passa Tempo Complex: crustal reworking under granulite facies conditions and collisional tectonics. Mafic-ultramafic layered intrusions (Carmópolis de Minas$^{(cms)}$; Ribeirão dos Motas). Basin tectonics. High grade metasedimentary rocks. Claudio shear zone. Post-tectonic to anorogenic plutons and basic dikes	Nd crustal derived isotopic signatures in granulitic rocks and migmatites. Chemical affinity of tholeiitic to calc-alkaline magmatism$^{(cms)}$ coupled with juvenile Nd isotopic signatures U–Pb ages (2.75 and 2.73 Ga) in detrital zircons from the Rio das Velhas greenstone belt. Local quartzites with restricted detrital age components (2.75 and 2.65 Ga)
Neoarchean 1: Rio das Velhas orogeny (early episode):	2.80–2.75$^{(cv)}$ (may include inherited ages up to 3.0)	Granite-greenstone terrain. Accretion the Bonfim and Belo Horizonte Complexes, and domic gneisses and migmatites in the Quadrilátero Ferrífero. Regional amphibolite facies conditions. Rio das Velhas greenstone belt volcanics. Island arc accreted to the Mesoarchean core	Gneissic rocks with juvenile-like Nd signatures (Bonfim and Belo Horizonte Complexes) with geochemical affinity with convergent margin setting of island arcs
Mesoarchean 2: Campo Belo orogeny	3.05–2.92 (including inherited ages). 2.84 Ga$^{(mg)}$	Progressive magmatic accretion (granite-greenstone terrain). Juvenile TTG gneisses and migmatites Campo Belo Complex and Santa Bárbara and Bação domes (Quadrilátero Ferrífero). Regional medium-grade metamorphism. Greenstone belts (dismembered): Piumhi, Rio Paraúna, Barbacena, Fortaleza de Minas	Juvenile-like Nd isotopic signatures. Pb inherited componentes in the Bonfim and Belo Horizonte Complexes. Regional distribution of Sm–Nd T_{DM} ages (3.2–3.0 Ga)
Mesoarchean 1: Campo Belo orogeny (includes the Santa Bárbara event)	3.22–3.20 (including inherited ages)	Juvenile generation of TTG gneisses (medium-to high grade terrain): Campo Belo Complex and Santa Bárbara dome	Protholiths of Paleoproterozoic gneisses (outboard the Quadrilátero Ferrífero)
Paleoarchean (Archean core)	>3.3	–	Pb-inherited age component in country rocks. U–Pb detrital zircon ages in supracrustal strata. Minor cluster of Sm–Nd T_{DM} ages (3.5–3.3 Ga)

Keys $^{(ih)}$inherited; $^{(zc)}$zircon core; $^{(pl)}$felsic plutons; $^{(mg)}$migmatization; $^{(cv)}$coeval felsic volcanism in the Rio das Velhas greenstone belt; $^{(cms)}$Carmópolis de Minas suite; $^{(gp)}$late-tectonic to anorogenic plutonism; $^{(ca)}$calc-alkaline(See Fig. 3.2 and text for details).

rocks (Minas Supergroup) ranging between 3.3 and 3.5 Ga, and one zircon core is as old as 3809 Ma, among other younger age peaks (Machado et al. 1996; Hartmann et al. 2006; Rosière et al. 2008; Moreira et al. 2016). Collectively these results offer a further clue for very ancient material as source for these units.

Detailed geological mapping with the support of zircon U–Pb geochronology, whole rock Nd–Sr isotopic and geochemical data is available for most of the Archean metamorphic complexes, as well as for two classical supracrustal units exposed in the Quadrilátero Ferrífero: (i) the Rio das Velhas Supergroup, an Archean greenstone belt that hosts world-class gold deposits (e.g., Ribeiro-Rodrigues 2001; Baltazar and Zucchetti 2007; Lobato et al. 2007 and references therein); and (ii) the Minas Supergroup (<2.58 Ga; Hartmann et al. 2006), an Early Paleoproterozoic platformal to syn-orogenic succession containing high-grade iron ore deposits hosted by a Lake Superior type banded iron formation (see Alkmim and Teixeira, this volume). Recent combined U–Pb and Lu–Hf isotope studies on detrital zircon and xenotime grains of the Moeda Group metaconglomerates and quartzites indicated that the sediments from the Minas Supergroup derived mainly from an evolved Archean continental crust (up to 3.3 Ga old) that was subjected to episodic crustal recycling and limited juvenile accretion (Koglin et al. 2014), i.e., the same sources of the underlying Archean Rio das Velhas Supergroup (see below). Moreover, the Archean and Paleoproterozoic supracrustal sequences and the TTG gneisses were largely affected by Paleoproterozoic metamorphism and extension tectonics dated between ca. 2.1 and 2.0 Ga. This event, usually known as the "Minas diastrophism" or "Transamazonian orogeny" (e.g., Alkmim and Noce 2006 and references therein), is now attributed to the Paleoproterozoic Minas accretionary orogen (e.g., Teixeira et al. 2015).

The protracted Archean history of the basement rocks agrees well with the idea of the existence of distinct crustal segments, originated through successive accretion episodes. In the next sections, we review the main geological and tectonic features of the Archean crust exposed in the southern portion of the SFC, bounded by the Paleoproterozoic Mineiro belt (Fig. 3.2). Therefore, a tectonic model is addressed, supported by the geochronological, isotopic and geochemical information. Two crustal segments can be distinguished in the region: (i) the Campo Belo metamorphic complex which includes a Mesoarchean inherited U–Pb age component first time identified in the southern SFC (Teixeira et al. 1998 and references therein) and a coeval remnant in the Quadrilátero Ferrífero known as the Santa Bárbara dome (Fig. 3.2); and (ii) the Belo Horizonte, Divinópolis, Bonfim, and Passa Tempo Complexes that constitute much of the Neoarchean continental crust.

3.3.1 The Mesoarchean Campo Belo Metamorphic Complex

The Campo Belo Complex (Fig. 3.3) is a medium to high-grade terrain, predominantly composed of amphibolite facies gray-greenish TTG orthogneisses, diorites, enderbites and pink granitic plutons. Migmatites are widespread, containing lenticular bodies of metabasites, often cut by aplites and pegmatites, and occasionally by Archean and Proterozoic mafic dykes (Teixeira et al. 2000). These country rocks typically exhibit a NS to NW-trending compositional banding. Within the Campo Belo Complex, relicts of clastic and chemical sedimentary units, which can host large graphite deposits, are locally exposed (e.g., Teixeira et al. 1996, 1998; Fernandes and Carneiro 2000; Oliveira and Carneiro 2001; Goulart et al. 2013) (Fig. 3.2).

Rb–Sr whole-rock isochron ages between 2904 ± 56 and 2881 ± 54 Ma with very low initial $^{87}Sr/^{86}Sr$ ratios (≤ 0.7018) in the nearby gneissic rocks of the Campo Belo Complex firstly indicated the occurrence of Mesoarchean crust in this portion of the SFC, as also suggested by compatible Pb evolution in a mantle-like reservoir with Pb-single stage (μ_1) = 8.18 (Teixeira et al. 1996 and references therein). Further U–Pb SHRIMP zircon dating by Teixeira et al. (1998) on a migmatite of the complex revealed three melting events. The oldest zircons yielded a concordant age of 3205 ± 25 Ma, interpreted as inherited age, reflecting the contribution of the primeval continental crust. A second concordant age cluster around 3047 ± 25 Ma was interpreted as recording the main accretion episode in the Campo Belo Complex. The youngest zircon population in the Campo Belo migmatite yielded 2840 ± 17 Ma, considered to be the crystallization age of the neosome. The observed variation of the $\varepsilon_{Nd(2.84\ Ga)}$ values (+0.9 and −3.0) is consistent with the identified melt generations in the migmatite. Therefore, the 3.2–2.9 Ga Campo Belo Complex originated from a juvenile accretionary process leading to a primeval continental core, which is here referred to as "the Campo Belo orogeny" for the first time. This tectonomagmatic episode matches in age with both the Santa Bárbara (ca. 3.21 Ga) and Rio das Velhas I (2.93–2.90 Ga) tectonic-magmatic events according to previous published U–Pb zircon ages in the Santa Bárbara dome (eastern portion of the Quadrilátero Ferrífero), as well as in the gneissic basement of the adjoining Proterozoic belt (Corrêa Neto et al. 2012; Noce et al. 2007c; Lana et al. 2013) (Fig. 3.2 and Table 3.1). In particular, the crystallization of the Santa Bárbara TTG gneisses is well constrained by U–Pb ages between 3210 ± 8 and 3212 ± 9 Ma (Lana et al. 2013). This provides the first direct evidence of the existence of an undisturbed ancient sialic crust in the southern SFC, previously inferred by the inherited U–Pb age component obtained in the Campo Belo migmatite (see above). In a

Fig. 3.3 **a** TTG-Orthogneisses of the Campo Belo Complex, exposed in quarry. **b** Key exposure of the Alberto Flores orthogneiss (2772 ± 6 Ma), the oldest lithostratigraphic unit of the Bonfim complex. Zircon cores from the orthogneiss are as old as 2.92 Ga. The Alberto Flores orthogneiss is cut by folded and weakly foliated dikes termed as Brumadinho granite (2702 ± 24 Ma) (Photo: E. P. Oliveira). **c** Field aspect of the Alberto Flores orthogneiss exhibiting a well developed N–S foliation, Neoarchean in age (Photo: E. P. Oliveira). **d** Field aspect of the Fontex stone quarry where the Neoarchean migmatite of the Divinópolis metamorphic Complex is locally rich in amphibolite boudins (Photo W. Teixeira). **e** Field aspect of the Guanhães TTG banded migmatitic gneiss exhibiting complex folding. **f** Banded trondhjemitic gneiss (2.90 Ga) exposed in the Serrinha quarry, southwestern Bação dome (Quadrilátero Ferrífero) (Photo: F. Alkmim)

similar manner, Lana et al. (2013) reported an identical U–Pb age on zircon cores (3213 ± 13) from a gneissic rock within the Quadrilátero Ferrífero. These crystallization ages, on the other hand, compare well with T_{DM} whole rock ages (3.2–3.0 Ga) and coupled juvenile-like $\varepsilon_{Nd(t)}$ values (see Teixeira et al. 2000 for review) for the gneissic-granitic rocks in the entire region, and point to the role of continental growth in Mesoarchean times (Teixeira et al. 2000, 2010; Silva et al. 2002, 2012b).

Scattered relicts of Mesoarchean greenstone belts (e.g., Piumhí, Fortaleza de Minas-Morro do Ferro, Barbacena and Rio Paraúna) crop out within the Proterozoic framework outside the craton boundaries. These units comprise strongly deformed and metamorphosed Mg-rich mafic and ultramafic volcanics, chemical and clastic sedimentary rocks. Some of the meta-igneous rocks have been dated by various methods, yielding ages between 3.2 and 2.9 Ga, as reviewed by Baars (1997). This suggests at first glance a tectonic relationship with the Campo Belo orogeny (see above). Notably, due to the scattered geographic distribution of these greenstone belt remnants, a larger extent for the Paleoarchean crust of the proto-SFC should be considered (Fig. 3.2). Table 3.2 presents the geologic-isotopic characteristics of the greenstone belt occurrences.

3.3.2 The Neoarchean Metamorphic Complexes

The Neoarchean gneisses and migmatites form much of the Archean crust. They include Mesoarchean dismembered amphibolites are intruded in places by tonalites, granodiorites and granites. They are usually deformed and metamorphosed under amphibolite facies conditions with greenschist facies

Table 3.2 Geologic-geochronologic characteristics of Mesoarchean greenstone belts in the southern SFC (see Fig. 3.2)

Greenstone belts	Distinguished geologic features	Age dating (Ma)	Occurrence/tectonics	References
Piumhí	Low grade metamorphic mafic-ultramafic rocks, volcaniclastics, intermediate lavas, chemical sedimentary rocks, intruded by felsic subvolcanic rocks. Interlayered sills of anorthosite-gabbro-piroxenite-peridotite. Late tectonic felsic intrusions	Anorthosite sill (U–Pb zircon age: 3116 ± 10); riodacitic intrusive dome ($^{207}Pb/^{206}Pb$ minimum ages: 3000 and 2965)	Uplift, allochthonous to paraauthocthonous volcanic-sedimentary sequence onto the Neoproterozoic cover. Crustal compression tectonically related with the Brasilia marginal belt	Alkmim (2004), Alkmim and Danderfer (1998)
Fortaleza de Minas-Morro do Ferro	Remnants of mafic and ultramafic rocks, chemical and clastic sedimentary rocks and tuffs, metamorphosed up to amphibolite facies	Basal komatiites (Sm–Nd whole rock isochron age: 2863 ± 65) Coeval migmatites (host rocks): Rb–Sr isochron age: 2918 ± 105	Dismembered tectonic slivers within an Archean basement inlier deeply reworked in Proterozoic times (basement of the Brasilia marginal belt). Greenstone rocks are in thermal equilibrium with nearby migmatites, both ductile deformed	Alkmim and Marshak (1998), Alkmim and Martins-Neto (2012)
Barbacena	Barbacena Group: differentiated mafic-ultramafic association (e.g., komatiites) and metasedimentary rocks, truncated by gabbroic dikes	Coeval, differentiated metakomatiites (Sm–Nd and Rb–Sr errorchrons between 3190 and 3220). Syntectonic intrusive trondhjemite (U–Pb inheritance of 3218 ± 16). Gabbroic dike (2706 ± 9 U–Pb age)	NE-trending greenstone association intermingled with basement rocks, syntectonically intruded by trondhjemite-tonalite rocks. Basement remnant within the Neoproterozoic marginal Ribeira belt	Alkmim and Noce (2006), Angelim (1997), Baars (1997)
Rio Paraúna	Rio Paraúna Supergroup: low- to medium grade metamorphic sequence: ultramafic to felsic metavolcanics, chemical (BIF) and clastic sediments, schist, phyllite, quartzite, metaconglomerate	Acid volcanic rock (U–Pb age of 2971 ± 8 Ma)	Tectonic slices of encompassing basement rocks, overlying the southern portion of the Espinhaço Supergroup. The supracrustal sequence is largely obliterated by Neoproterozoic compression (Araçuaí belt)	Baltazar and Zucchetti (2007), Barbosa et al. (2008, 2012)

overprint (Machado et al. 1992; Teixeira et al. 2000; Romano et al. 2013; Lana et al. 2013) (Fig. 3.3). In conjunction with the Rio das Velhas greenstone belt in the Quadrilátero Ferrífero the basement rocks make up an extensive granite-greenstone terrain in the southern portion of the SFC (e.g., Baars 1997; Noce et al. 2007c; Lobato et al. 2007). From a tectonic perspective, the Quadrilátero Ferrí-fero shows a characteristic dome and keel geometry (Marshak et al. 1992 and references therein), highlighted by gneiss domes of granitic, granodioritic and tonalitic composition, and subordinate migmatites encircled by supracrustal sequences (e.g., Rio das Velhas and Minas Supergroups. The domes are locally known as Florestal, Caeté and Bação domes and composed essentially of banded gneisses and migmatites (Fig. 3.2). To the southwest of the Quadrilátero Ferrífero, the Neoarchean crust is composed of medium to high-grade TTG-gneisses locally referred to as Bonfim, Belo Horizonte, Divinópolis and Passa Tempo Complexes with coeval metasedimentary remnants. The geologic relationships between these metamorphic complexes are still tentative, due to polyphase deformation, metamorphism in Archean and Proterozoic times, as well as intensive weathering. These complexes are, on the other hand, crosscut to the west by the Claudio Shear Zone (see above and Fig. 3.2).

The Bonfim Complex (Fig. 3.2) includes two types of amphibolite facies, banded gneisses with strongly deformed, dismembered amphibolites and locally sheared tonalites. Weakly foliated and folded K-rich aplites crosscut the regional foliation of the country rocks (Fig. 3.3a–c). The oldest orthogneiss (Alberto Flores) shows geochemical composition akin to the high Al_2O_3 TTG rock suite, whereas the younger Souza Noschese granitic gneiss, which is intrusive into the Alberto Flores orthogneiss, shows geochemical signature suggestive of derivation from partial melting of trondhjemitic crust (Carneiro et al. 1998; Machado and Carneiro 1992 and references therein).

The lithostratigraphy of the Belo Horizonte Complex (Fig. 3.3) is lesser known than that of the Bonfim Complex (Machado and Carneiro 1992; Noce et al. 1997, 1998; Silva et al. 2012a). The Belo Horizonte Complex consists essentially of banded orthogneisses with amphibolite xenoliths and deformed aplites and felsic veins. Migmatites are very common. These rocks locally show a well-developed, NS-striking, low angle mylonitic foliation, which is also characteristic of the adjoining Guanhães gneissic-migmatitic complex and the Bação gneissic dome (Fig. 3.3a, d, e). The less migmatized orthogneisses of the complex shows a predominantly trondhjemitic composition and a REE pattern comparable with that of the nearby Bonfim and Bação complexes.

The Belo Horizonte Complex was originally dated at 2860 ± 17 Ma (ID-TIMS U–Pb) in zircon from a leucossome of a migmatitic gneiss. An inherited $^{207}Pb/^{206}Pb$ age component yielded 2.92 Ga (Noce et al. 1998). New U–Pb SHRIMP ages on both igneous zircon cores and overgrowths recovered from the same outcrop (Silva et al. 2012b) indicated an upper intercept of a concordia diagram with an age of 2787 ± 14 Ma that defines the crystallization of the magmatic precursor of this gneiss. The previous published U–Pb age is therefore probably a mixed result.

The Passa Tempo Complex comprises granulite facies rocks showing regional high-grade ductile deformation. The granulitic complex, limited to the south by the Jeceaba-Bom Sucesso lineament Fig. 3.2), occurs along the southern end of the Claudio shear zone (Campos et al. 2003 and references therein). The Passa Tempo complex mainly comprises hypersthene-bearing gneissic rocks (mainly charnockite and enderbite), showing characteristic NNW layering. Subordinate lens-shaped serpertinites and gabbros are remarkable, where local boudinage and small shear bands affect the mafic and mafic-ultramafic rocks. Charnockites and enderbites (Engler et al. 2002) that are widespread in the neighborhoods of Lavras and Perdões, close to the inferred limit with the Campo Belo Complex, can be also assigned to the Passa Tempo Complex. In this area migmatites are subordinate, whereas granodioritic to alkali-granitic plutons are locally present. These plutons are products of crustal anatexis, which is coeval with the high-grade metamorphism (Engler et al. 2002). According to these authors, the Passa Tempo rocks usually exhibit a regional retrograde amphibolite facies metamorphism (PT conditions of 600–700 °C and 5–6 kb) with a later weak greenschist facies overprint. The latter episode is considered here to signalize the time of the last uplift of the region. The charnockites exhibit REE patterns characteristic of K-rich granites, and were produced by partial melting of TTG crust. This process must have taken place at less than 40 km depth, where plagioclase is a stable residual phase. By contrast, the enderbites, which are interpreted as part of a bimodal suite, were formed through a dual phase partial melting process at mantle or lower crustal depths, where garnet occurs as a stable residual phase.

The main Neoarchean metavolcanic-sedimentary association (Rio das Velhas Supergroup) occurs in the Quadrilátero Ferrífero and in the region to the west of it, in the vicinity of Pará de Minas and Florestal. This unit constitutes a tectonically dismembered, strongly hydrothermally altered greenstone belt that hosts world-class gold deposits (e.g., Schorscher et al. 1982; Ribeiro-Rodrigues 2001; Baltazar and Zucchetti 2007; Lobato et al. 2007; Noce et al. 2007c). The Rio das Velhas Supergroup is subdivided from base to top into the Nova Lima and Maquiné groups. The lower unit is composed of ultramafic and mafic volcanic rocks, minor felsic volcanics, as well as chemical and clastic sedimentary rocks (Fig. 3.4 a, b). From the tectonic point of view, the Rio das Velhas Supergroup is coeval with the Bonfim and Belo

Fig. 3.4 Rocks of the Rio das Velhas greenstone belt succession. **a** Komatiite of the basal portion of the Rio das Velhas Supergroup showing spinifex texture (Photo: F. Alkmim). **b** Deformed pillow lavas of the basal Rio das Velhas greenstone belt succession. **c** Cross-bedded quartzite of the clastic upper portion of the Nova Lima Group (Photo: C.M. Noce). **d** Ribeirão dos Motas stratiform sequence (ca. 2.70 Ga old): the composition of the subhorizontal ultramafic layers ranges from peridotite to pyroxenite (Photo: M.A. Carneiro)

Horizonte Complexes (Fig. 3.2). Collectively this Neoarchean granite-greenstone terrain was affected by the so-called Rio das Velhas orogeny (e.g., Machado et al. 1992; Machado and Carneiro 1992; Teixeira et al. 2000 and references therein).

Scattered mafic-ultramafic layered bodies occur in the southern SFC, such as the Carmópolis de Minas Suite and the Ribeirão dos Motas stratiform sequence. The Carmópolis de Minas Suite, intrusive into the Passa Tempo metamorphic complex, occurs not far from the southernmost end of the Claudio Shear Zone. According to Goulart et al. (2013), it consists of a layered and massive plutonic or sub-volcanic, mafic-ultramafic to felsic association, complexly deformed and metamorphosed under upper amphibolite-granulite facies conditions (like the Passa Tempo metamorphic complex), and includes rocks with tholeiitic and calc-alkaline affinity. U–Pb zircon ages for amphibolite and meta-rhyolite from this suite indicated crystallization ages of 2752 ± 18 and 2713 ± 10 Ma respectively, with a number of inherited grains of Mesoarchean age (Table 3.1). Very subordinate metasedimentary rocks crop out close to the Carmópolis de Minas Suite, occasionally intercalated with the amphibolite lenses. The nearby Ribeirão dos Motas stratiform sequence comprises slightly deformed and metamorphosed layers of peridotite and pyroxenite, and subordinate amphibolite and gabbronorite (Fig. 3.4c). This sequence was emplaced at ca. 2.79 ± 0.3 Ga ($\varepsilon_{Nd(t)} = +0.5$), as indicated by a Sm–Nd whole rock isochron using several of the lithotypes (Carneiro et al. 2004).

Granulite facies metamorphism predominates over the ultramafic rocks, overprinted by amphibolite and greenschist facies paragenesis (Fernandes and Carneiro 2000). Locally, the Ribeirão dos Motas rocks were affected by dextral mylonitic foliation related to the Claudio Shear Zone (Carneiro et al. 1997).

3.3.3 Crustal Evolution

Available U–Pb ages and geochemical data for medium- to high-K granitoids and orthogneisses (2920–2850, 2800–2760 Ma, 2750–2720 Ma) in the Quadrilátero Ferrífero and surroundings characterize not only the polycyclic nature of the Meso- and Neoarchean continental crust of the southern SFC (as old as 3.3 Ga), as already demonstrated by Lana et al. (2013), but also a major change in the composition that reflect melting of different sources through time (Farina et al. 2015). Considering the Neoarchean era, the isotopic and geochemical data on basement rocks, and granitic and mafic-ultramafic intrusions (e.g., Teixeira et al. 2000; Goulart et al. 2013; Romano et al. 2013; W. Teixeira, unpublished data) suggest that the Rio das Velhas orogeny (after Machado and Carneiro 1992) would include two distinct crustal growth episodes dated at ca. 2790–2750 and 2730–2700 Ma (Tables 3.1, 3.2 and Fig. 3.2).

The early Neoarchean episode originated the extensive granite-greenstone terrain, represented by the Bonfim and Belo Horizonte complexes and nearby (domed) gneisses (e.g., Florestal, Caeté, Bação), to which the Rio das Velhas Supergroup is genetically related (e.g., Machado et al. 1992; Teixeira et al. 1996; Campos et al. 2003; Romano et al. 2013; Lana et al. 2013). For instance, the Alberto Flores orthogneiss (Bonfim complex) yields U–Pb crystallization age of 2772 ± 6 Ma (zircon overgrowth), whereas the zircon core gives 2.92 Ga, which is considered a minimum age for the protolith (Machado and Carneiro 1992; Teixeira et al. 2000). This hypothesis agrees well with a group of whole rock Sm–Nd T_{DM} ages (2.80–2.94 Ga) in gneissic rocks of the southern SFC, as well as with recently published U–Pb zircon ages in the Quadrilatero Ferrífero rocks (Farina et al. 2015). The bulk REE pattern and $\varepsilon_{Nd(t)}$ isotopic characteristics of these rocks are consistent with juvenile accretion in a convergent margin setting (e.g., Machado and Carneiro 1992). Specifically the Samambaia intrusive tonalitic gneiss (Bação complex), which encloses mafic volcanics (now amphibolites), yields U–Pb zircon and titanite ages of 2780 +3/−2 Ma and 2774 ± 6 Ma respectively. The slightly negative $\varepsilon_{Nd(t)}$ values calculated for the Bonfim gneisses and amphibolites suggest that much of the crust formed during the 2780–2700 Ma orogenic episode (Teixeira et al. 1996 and references therein). Granodioritic to granitic plutons, such as the Mamona Granitoid and the Brumadinho granitic aplite yield U–Pb ages of 2721 ± 3 and 2703 ± 24/−20 Ma, respectively, and are related to the late-tectonic evolution of the Bonfim complex (e.g., Machado and Carneiro 1992; Alkmim and Noce 2006; Farina et al. 2015)—see below. The Belo Horizonte Complex (2787 ± 14 Ma; Silva et al. 2012a) can be similarly attributed to the early episode of the Rio das Velhas orogeny (Table 3.1).

The generation of such a continental crust (e.g., Belo Horizonte and Bonfim complexes) is roughly concomitant with various granitic plutons in the Quadrilátero Ferrífero region, as well as with felsic volcanics and deposition of siliciclastic rocks in the Rio das Velhas greenstone belt (Noce et al. 1997; Hartmann et al. 2006). For instance, Campos and Carneiro (2008) first demonstrated that the oldest production of TTG crust (ca 2780–2770 Ma) is a regional scale phenomenon (see Table 3.1). According to the same authors, these plutons mainly derived by juvenile accretion at the time, although a few inherited zircon ages (up to 3.0 Ga) indicate that Mesoarchean crust was assimilated during magma genesis, as also suggested by low negative $\varepsilon_{Nd(t)}$ values (see Table 3.1). Some migmatitic gneisses outcropping to the west of the Belo Horizonte and Bonfim Complexes, locally affected by the Claudio Shear Zone (Fig. 3.2), can be tentatively attributed to the early episode of the Rio das Velhas orogeny due to their U–Pb zircon ages (upper intercept with the Concordia) between 2765 and 2750 Ma. These migmatitic gneisses contain again a number of 2.90 Ga inherited zircon grains, in a similar way to the Bonfim and Belo Horizonte rocks (Oliveira 2004).

Lana et al. (2013) reported a detailed U–Pb survey on Neoarchean TTG gneisses and granitoids in the Quadrilátero Ferrífero and surroundings. They confirmed that the main magmatism, deformation and amphibolite-facies metamorphism took place between 2800 and 2770 Ma—attributed to their Rio das Velhas II event. According to these authors, the available geologic and isotopic evidences support a model in which both the TTG rocks and the Rio das Velhas volcanics are genetically related with an island arc accreted to the Mesoarchean continental margin. This model was recently demonstrated by detailed U–Pb work on distint lithoestratigraphic units of the Rio das Velhas Supergroup (e.g., Moreira et al. 2016), indicating the Meso- and Neoarchean basement rocks as the main sources (Fig. 3.5). Few significantly older detrital zircons from the siliciclastic sequences were also reported by Hartmann et al. (2006).

The youngest detrital zircon grains of the Maquiné Group (upper unit of the Rio das Velhas Supergroup) yield ages between 2718 ± 17 Ma (concordant) and 2746 ± 6 (−2 % discordance) and 2749 ± 6 Ma (1 % discordance), determining the maximum depositional age and the terminal evolutional stage of the Rio das Velhas greenstone belt (Hartmann et al. 2006; Moreira et al. 2016). U–Pb zircon ages of felsic volcanics concomitant with the deposition of the Nova Lima Group sediments (Rio das Velhas greenstone belt) defined three eruption episodes at ca. 2792 ± 11, 2773 ± 7 and 2751 ± 9 Ma (Fig. 3.5), suggesting a range of about 40 Ma for the eruptives (Machado et al. 1992; Noce et al. 1997 and references therein). This time interval is therefore consistent with the first episode of the Rio das Velhas orogeny suggested

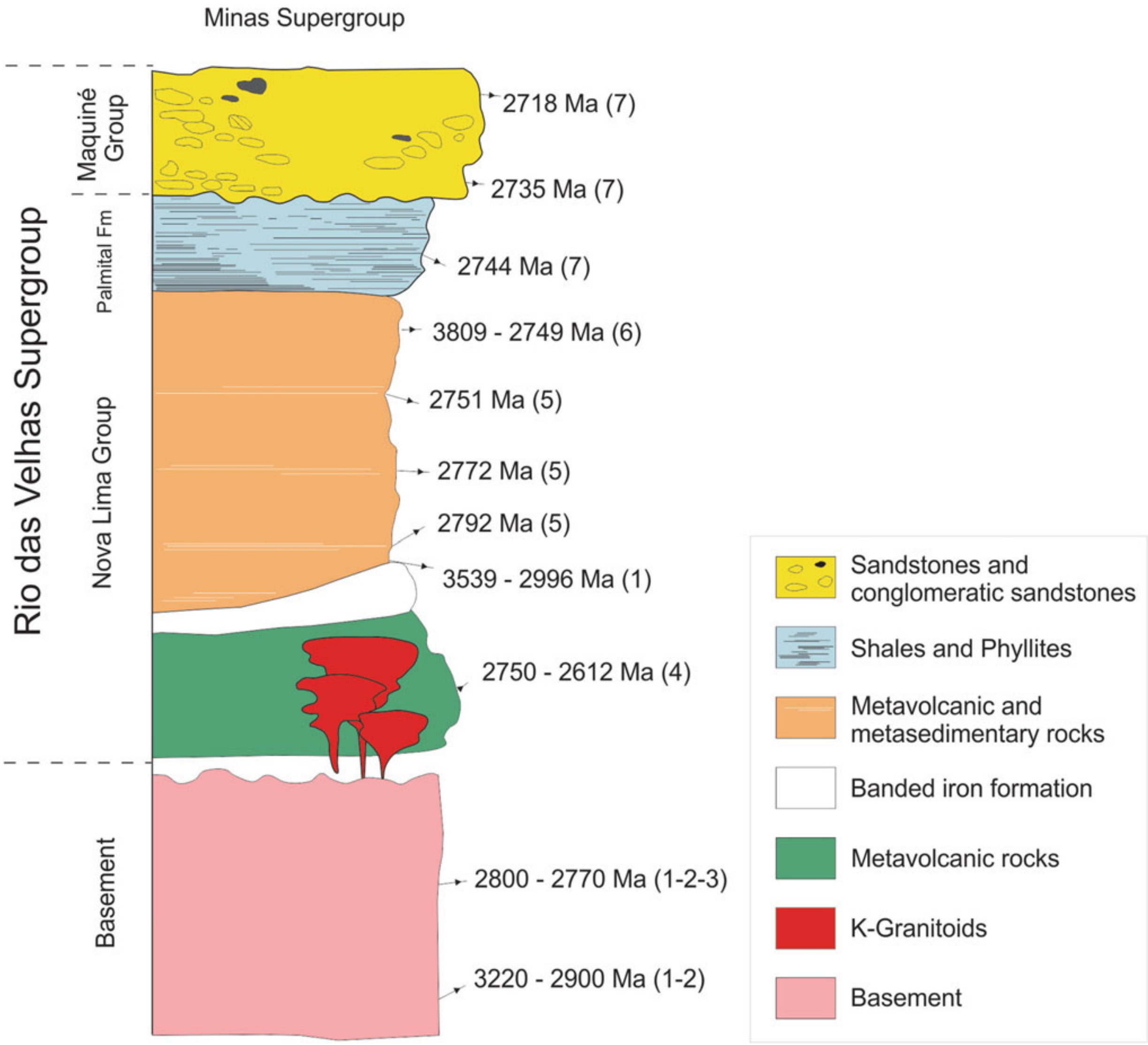

Fig. 3.5 Stratigraphic column of the Rio das Velhas Supergroup (after Moreira et al. 2016 and references therein). Numbers in parentheses after the age data are referred to: (1) Machado et al. (1996); (2) Lana et al. (2013); (3) Machado et al. (1992); (4) Romano et al. (2013); (5) Noce et al. (2005); (6) Hartmann et al. (2006); (7) Moreira et al. (2016)

in this work (Table 3.1). The two oldest volcanic pulses match in age the nearby tonalitic-granodioritic intrusions (e.g. Caeté and Bonfim Complexes), which yielded U–Pb crystallization ages of 2776 +7/−6 Ma and 2780 +3/−2 Ma respectively (Machado et al. 1992; Machado and Carneiro 1992). These plutons are partly or totally emplaced into the domed Archean gneissic-granitic complexes encircled by the Rio das Velhas greenstone belt (Noce et al. 1998). In the Caeté dome (Fig. 3.2), a deformed felsic volcanic rock of the Rio das Velhas Supergroup has inherited zircons that yielded a slightly discordant $^{207}Pb/^{206}Pb$ age of 3029 ± 6 Ma. Therefore, this is again an indirect evidence of a Mesoarchean precursor continental source (e.g., Machado and Noce 1993) in accordance with previous published U–Pb dating for the Bonfim and Belo Horizonte Complexes, including Hf zircon isotopic evidence (Koglin et al. 2014)—see Sect. 3.3.

Ore samples of the Morro Velho and Cuiabá gold deposits yield a U–Pb SHRIMP Concordia age of 2672 ± 14 Ma on hydrothermal monazite grains, which defines the timing of mineralization associated with the Rio das Velhas Supergroup (Lobato et al. 2007). However, Tassinari et al. (2013) report a much younger gold remobilization event under medium grade metamorphism (2.2–2.1 Ga) at the northwestern occurrence of the greenstone belt.

Noce et al. (1997) first evaluated the role of granitic plutons in the Late Archean evolution in southern SFC based on geologic information and U–Pb isotopic evidence, distinguishing three generations of plutons dated at ca. 2780–2760; 2720–2700 and 2600 Ma. Among these events, the younger pulses are considered of crustal origin (e.g., Campos and Carneiro 2008). More recently, Romano et al. (2013) defined two consecutive pulses of K-rich granitic rocks in neighborhoods of the Quadrilátero Ferrífero, dated at 2760–2750 and 2730–2700 Ma. Specifically, the Bação dome (Fig. 3.2), which consists of 2925 ± 5 to 2715 ± 5 Ma TTG gneisses and potassic granitoids, could indicate the ultimate accretion in an island arc setting close to the Mesoarchean landmass, as envisaged by Lana et al. (2013). According to this model the peculiar high-K rocks of the southern SFC should record the final cratonization and consolidation of the continental crust between 2750 and 2720 Ma (Farina et al. 2015). From the above, we suggest the youngest and widespread Neoarchean plutonism of the latest episode of the Rio das Velhas orogeny postulated here (see Table 3.1), as markers of progressive nucleation of the continental mass. This episode probably includes calc-alkaline magmatism (e.g., Carmópolis de Minas layered intrusion) and subsequent high-grade metamorphism having the imprint of polyphase deformation and crustal anatexis (e.g., Passa Tempo granulitic complex) (see above and Fig. 3.2).

The Carmópolis de Minas Layered Suite (2752–2713 Ma) shows predominant low Mg# values that coupled with the presence of low-K_2O rocks in close association with metasedimentary remnants suggest that the protolith may have been derived from evolved magmas in an oceanic arc setting. Specifically, the amphibolite and metarhyolite show slightly positive to slightly negative $\varepsilon_{Nd(t)}$ values respectively, pointing to the involvement of two magmatic sources (restricted to ca. 40 Ma) such as depleted mantle reservoirs and/or enriched mantle sources (Goulart et al. 2013).

We suggest that the Carmópolis de Minas Suite could be related with the Neoarchean arc accreted to the Mesoarchean continental core (i.e., Campo Belo and Santa Barbara complexes), in roughly agreement with the tectonic model of Moreira et al. (2016). During this event a syn-orogenic, tholeiitic phase was shortly followed by sub-arc crustal anatexis to allow for calc-alkaline melts and crustal reworking of short-lived material (Goulart and Carneiro 2013). In other words, there is again evidence for the latest accretionary episode of the Rio das Velhas orogeny postulated here (see Table 3.1). In consequence, the evolving magmatic arc contributed to the ultimate crustal growth of the Neoarchean landmass, as also reflected by a widespread granite-genesis at that time (Noce et al. 1997; Romano et al. 2013).

The ca. 2.7 ± 0.3 Ga Ribeirão dos Motas stratiform sequence that crops out near the Carmópolis de Minas Suite shows a positive $\varepsilon_{Nd(t)}$ value (+0.5) that suggests a derivation from a slightly enriched magma source. The isotopic evidence allows a genetic relationship with the slab subduction process that formed the Carmópolis de Minas Suite (see above). However, the Ribeirão dos Motas mafic-ultramafic rocks show high MgO, Cr, and Ni contents and relatively low SiO_2, TiO_2, K_2O and REE elements akin to komatiite magmas or high magnesian basalts (Carneiro et al. 1997). This geochemical signature is consistent with our hypothesis of partial melting of a peculiar mantle source pertinent to the late episode of the Rio das Velhas orogeny (Table 3.1).

The minimum age for the granulitic facies metamorphism and migmatization of the Passa Tempo complex was first estimated at 2661 ± 36 Ma (Rb–Sr whole rock isochron; Teixeira et al. 1998) later supported by U–Pb dating with an upper intercept of a concordia diagram at 2622 ± 18 Ma (Campos et al. 2003). New U–Pb concordant or nearly concordant zircon U–Pb ages for the Passa Tempo migmatites and gneisses predominating nearby Lavras indicate identical, within error, ages of 2715 ± 12, 2701 ± 5 and 2682 ± 15 Ma (W. Teixeira, unpublished data). These data also determine a reliable age for the anatexis of the Passa Tempo Complex. The rocks yield variable negative $\varepsilon_{Nd(2.70\ Ga)}$ values between −5.1 and −1.5 indicating the important role of crustal reworking at that time (Oliveira 2004; W. Teixeira, unpublished data).

From a geodynamic point of view, development of partial crustal melting under granulite facies concomitant with horizontal shortening is an unequivocal evidence of a compressional setting, syn-kinematic with the 2730–2700 Ma episode of the Rio das Velhas orogeny (see above and Table 3.1). This is also consistent with the nearby occurrence of a large layered mafic-ultramafic intrusions (Carmópolis de Minas, Ribeirão dos Motas) that requires emplacement conditions into a thickened continental crust, now exposed as a deeply eroded root zone (i.e., Passa Tempo granulitic rocks). As a corollary, the geologic boundary between the Neoarchean sialic fragment and the Mesoarchean one (i.e., Campo Belo Complex) is probably obliterated.

Between 2615 and 2550 Ma crustal derived granite plutons (Table 3.1) intruded the Archean substratum of the southern SFC (Noce et al. 1997; Campos and Carneiro 2008; Romano et al. 2013). They were emplaced under brittle-ductile, dextral transpressional conditions with tectonic transport from NE to SW (Rio das Velhas III event; Table 3.1 in Campos et al. 2003). Such a tectonic framework, according to these authors, indicates that a potential continent-continent collision event occurred at the late Archean, as also suggested by the structural/metamorphic framework of the Passa Tempo Complex. In this regard, we suggest that the Claudio Shear Zone with dextral transpression kinematics overprinting coeval migmatitic rocks along the western edge of the Bonfim Complex could be tentatively considered as the collisional front. In other words, the crustal derived granites would indicate the last remobilization and thickening of the continental crust, leading to a coherent, tectonically stable Neoarchean landmass (e.g., Noce et al. 1997, 1998; Romano et al. 2013) (Table 3.1; Fig. 3.2). This coherent lithosphere eventually allowed deposition of the Minas Supergroup in the passive margin setting (e.g. Alkmim and Noce 2006 and references therein). The evolutionary stage was accompanied by extensional tectonics with emplacement of NW-trending, noritic-gabbroic dikes dated at 2658 ± 44 Ma (Sm–Nd isochron; Pinese et al. 1995). This peculiar swarm transects both the Campo Belo metamorphic complex and the Ribeirão dos Motas mafic-ultramafic layered body (Table 3.1).

Final regional cooling of the gneissic-granitic complexes occurred between ca. 2.1–1.9 Ga, as supported by K–Ar and ^{40}Ar-^{39}Ar geochronology over the metamorphic complexes to the west of the Quadrilátero Ferrífero (e.g., Teixeira 1982; Teixeira et al. 1997, 2000; Oliveira 2004). Crustal exhumation occurred concomitantly with Paleoproterozoic retrograde metamorphism overprinting the basement rocks, as well as fold-thrust tectonics as a response from an outboard accretionary orogenic event (Machado et al. 1992; Alkmim and Marshak 1998; Teixeira et al. 2000; Oliveira 2004) (for details see Alkmim and Teixeira, this book).

3.4 Archean Assemblages of the Northern Portion of the Craton

A large number of Archean gneissic migmatitic rocks, granulites, greenstone belts and granitoids makes up the crystalline basement of the northern SFC, which consists of various sialic blocks (Gavião, Sobradinho, Serrinha and Jequié blocks, see Fig. 3.1). This portion of crust was partially or intensively affected by Paleoproterozoic metamorphism and deformation (Barbosa et al. 2012, and references therein) in a similar manner as the southern lobe of the craton.

Two distinct Archean domains separated by the Paleoproterozoic Contendas-Jacobina Lineament (or shear zone) (Fig. 3.6) can be distinguished on tectonic grounds (Barbosa and Sabaté 2004 and references therein): (i) a western domain corresponding to the Gavião Block and its potential northern correlative, the Sobradinho Block; and (ii) an eastern domain that includes the Serrinha and Jequié Blocks, intensively affected by a Paleoproterozoic collisional event responsible for the development of the Itabuna–Salvador–Curaçá belt (see Barbosa and Barbosa, this book).

3.4.1 The Gavião and Sobradinho Blocks

The Gavião Block is one of the most important areas to understand the early crustal evolution in South America, given the extensive exposures of the oldest rocks within the SFC. It is composed of a variety of TTG gray gneisses and migmatites, granites, and dismembered greenstone belt associations (Fig. 3.6). The block is bounded to the east by the Paleoproterozoic Contendas-Jacobina Lineament and to the south by the Neoproterozoic Araçuaí belt. Relicts of the Gavião Block may also form the crystalline basement of volcanic-metasedimentary sequences, such as the Sete Voltas and Boa Vista gneissic domes (Fig. 3.7a) within the Contendas-Mirante supracrustal belt.

The Gavião Block is overlain by metasedimentary sequences of the Paleo/Mesoproterozoic Espinhaço Supergroup and the Neoproterozoic platformal Bambuí Group and correlative units (e.g., Barbosa et al. 2012 and references therein). Of note, basement rocks along the Paramirim aulacogen (Alkmim and Danderfer 1998) at the northwestern portion of the Gavião Block (Fig. 3.1) were thrust over the Espinhaço sequence due to far-field stresses developed during the evolution of the Neoproterozoic Araçuaí belt marginally to the SFC.

3.4.1.1 Granite-Gneissic Terrains

Detailed geologic-geochronologic studies on the Gavião Block have established a protracted evolution from the Paleoarchean to the Neoarchean (Table 3.3), similar to the evolution of the southern SFC. The continental crust formed in the Paleo- and Mesoarchean underwent metamorphism and partial recycling into migmatites and granites between 2.7 and 2.6 Ga (Santos-Pinto et al. 2012). In addition, the Gavião Block includes some of the oldest juvenile granitoid rocks, TTG orthogneisses of the SFC, dated between 3650–3260 and 3180–3000 Ma (Nutman and Cordani 1993; Martin et al. 1997; Peucat et al. 2002; Dantas et al. 2013). Indirect evidence for a Hadean primeval crust (4.1 Ga) is also noticeable by the detrital zircon age in one supracrustal sequence of the Gavião Block. This is also consistent with previously published Sm–Nd T_{DM} model ages on orthogneisses from the same domain (Paquette et al. 2015).

Most of these ancient granitoids intrude or encompass ancient metavolcanic-sedimentary sequences that are scattered over the Gavião Block such as the Ibitira-Ubiraçaba, Mundo Novo and Guajeru greenstone belts (Leahy et al. 1999; Nutman and Cordani 1993; Leal et al. 1996) (Fig. 3.6). Moreover, they constitute the crystalline basement (i.e., the Santa Isabel and Riacho de Santana Complexes) of the Paleoproterozoic Riacho de Santana

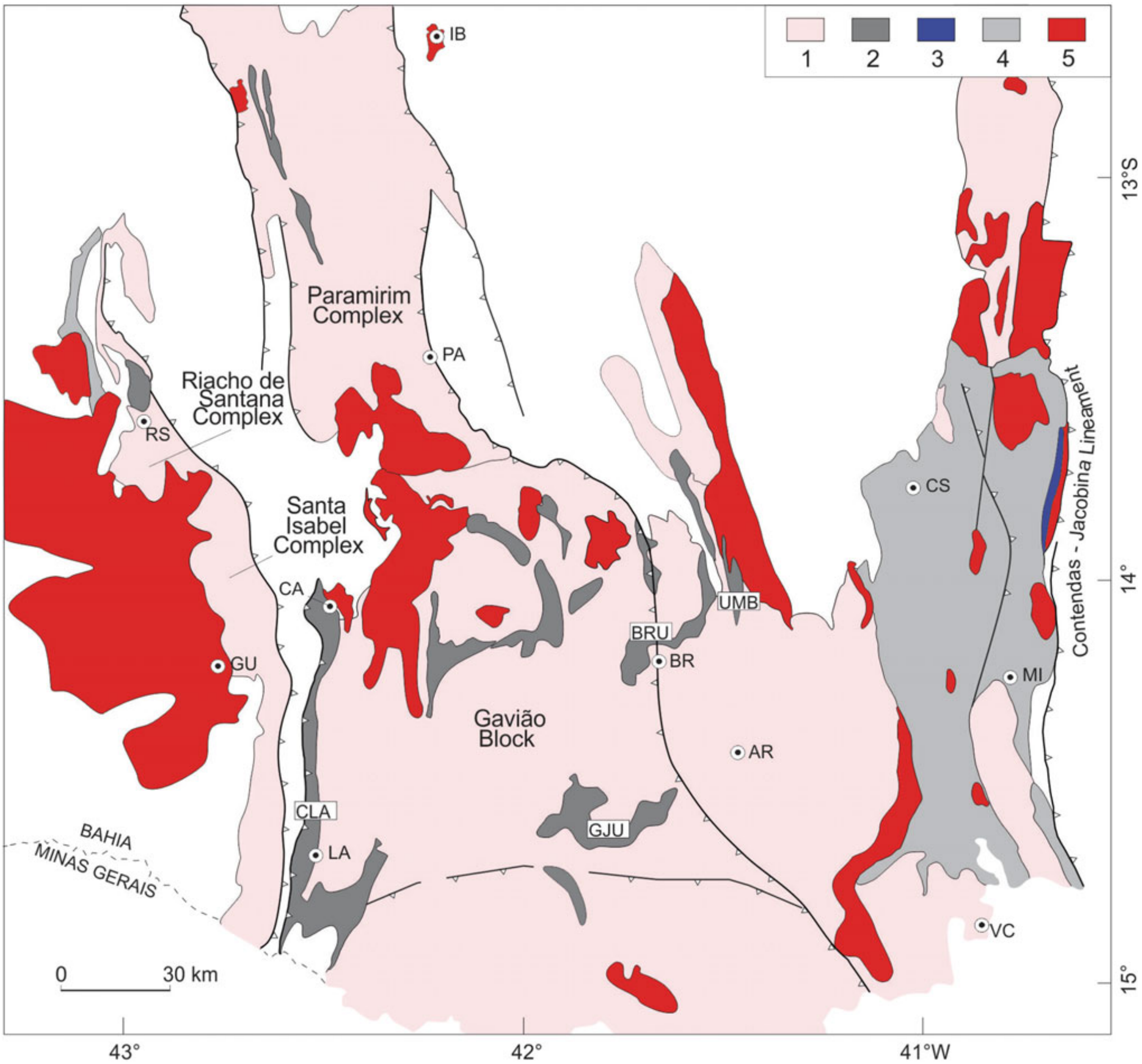

Fig. 3.6 Geologic sketch of the northern portion of the SFC showing the Archean Gavião Block and adjacent terrains, articulated by the Contendas-Jacobina Lineament—CJL (adapted from Barbosa et al. 2012). *1* Archean basement including the Santa Isabel (CSI), Riacho de Santana (RC), and Paramirim (CPA) Complexes and unnamed TTG gneisses and migmatites (CGV), and granitoid rocks. *2* Volcanic-sedimentary sequences including greenstone belts [e.g., Caetité-Licínio de Almeida (*CLA*), Brumado (*BRU*), Guajerú (*GJU*), Umburanas (*UMB*)]; *3* Rio Jacaré sill; *4* Archean-Paleoproterozoic volcanic-sedimentary sequences (e.g. Contendas Mirante); *5* Paleoproterozoic granitoid rocks; *6* cover. Towns: RS (Riacho de Santana), GU (Guanambi), LA (Licínio de Almeida), CA (Caetité), IB (Ibitiara), PA (Paramirim), BR (Brumado), AR (Aracatu), CS (Contendas do Sincorá), MI (Mirante), VC (Vitória da Conquista). See text for details

greenstone belt occurring in the western portion of the Block (Barbosa et al. 2013 and references therein).

Rocks of the oldest age group (3650–3260 Ma) are common in the western, central and eastern border of the Gavião Block, such as the the gneissic-migmatites of the Riacho de Santana Complex, the Sete Voltas and Boa Vista gneissic domes and associated felsic volcanics. The Riacho de Santana Complex (Fig. 3.6; Table 3.3) is the oldest fragment so far recognized in the Block. It yields a ID-TIMS U–Pb zircon upper intercept crystallization age of 3648 ± 69 Ma and Sm–Nd T_{DM} model age of 3.9 Ga; its negative $\varepsilon_{Nd(t)}$ value is compatible with a protracted history which included a migmatization episode dated at 3.25 Ga (Barbosa et al. 2013). In a similar manner, the Sete Voltas gneissic dome shows a polycyclic evolution, highlighted by TTG gneiss xenoliths as old as 3403 Ma (Sm–Nd T_{DM} age = 3.6–3.7 Ga) within

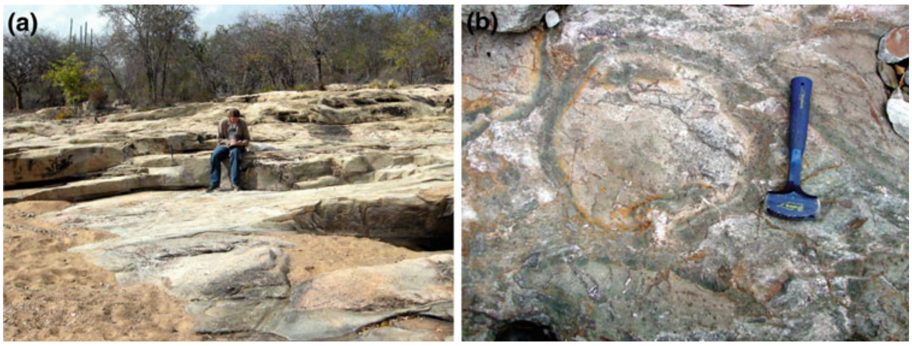

Fig. 3.7 **a** Gneissic rocks of the eastern margin of the Paleoarchean Sete Voltas basement dome, where the tonalitic orthogneiss shows E-dipping foliation (Photo: E.P. Oliveira). **b** Pillow basalt of the Paleoarchean Mundo Novo greenstone belt, Cachoeira da Fumaça (Pindobaçu, Bahia) (Photo E.P. Oliveira)

Table 3.3 Characteristics of the Archean evolution and Paleoproterozoic assembly of the northern SFC

Events	U–Pb age range (Ga)	Geologic-tectonic features	Geochemical and isotopic constraints
Early Proterozoic; continental and oceanic arcs	2.17–2.04	Ocean closure, island arcs, collision and reworking of Archean blocks, high-grade metamorphism, terrane extrusion (Uauá block), final formation of the Itabuna-Salvador-Curaçá orogeny	Juvenile Nd isotope data, calc-alkaline signature, metamorphic zircon U–Pb ages
Neoarchean 2: Caraíba	2.65–2.56	Caraíba Complex: continental margin arc batholiths, mafic-ultramafic intrusions (São José do Jacuipe layered anorthosite, Caraiba norite-pyroxenite complex, Rio do Jacaré gabbroic sill). Uauá tholeiite dike swarm. Late granitoids in the Gavião Block	Juvenile to crustal Nd isotope signatures and calc-alkaline geochemistry of Caraíba orthogranulites
Neoarchean 1: Jequié	2.80–2.70	Late tectonic granitoids in the Gavião Block, granites of the Jequié Block, Uauá norite dikes, Pedra Preta chromitiferous serpentinite body	Gneissic rocks with juvenile-like Nd signatures (Jequié complex) with geochemical affinity with continental and oceanic arcs
Mesoarchean: Serrinha-Uauá	3.20–2.98	Serrinha TTG gneisses, Uauá-Capim granitoids, high-grade orthogneisses and Santa Isabel gneisses (Gavião Block). Lagoa da Vaca anorthosite. Granitoid rocks in the Gavião Block	TTG geochemical signatures and juveline Nd isotope signatures
Paleoarchean: Sobradinho and Sete Voltas	3.40–3.26	Greenstone belts (Mundo Novo, in the Gavião Block, Lagoa do Alegre in the Sobradinho Block), TTG plutons and gneisses (Sete Voltas dome), and dacite in the Contendas-Mirante supracrustal belt	Zircon U–Pb ages and Nd–Hf signatures
Paleoarchean to Eoarchean: Enclaves	3.5–3.7	Ancient gneiss-migmatite complexes (e.g., Riacho de Santana gneissic-migmatitic Complex and gabbro-diorite enclaves in Sobradinho migmatitic gneiss)	Zircon U–Pb and Hf ages of diorite enclaves in migmatite (Sobradinho Block), and inherited zircon in the Paleoproterozoic Quijinge granite (Rio Itapicuru greenstone belt)

See text for details

3243 Ma porphyritic granodiorite (T_{DM} age = 3.5–3.7 Ga), or in 3158 Ma gray gneiss (T_{DM} age = 3.5–3.6 Ga). Both country rocks also yield slightly negative $\varepsilon_{Nd(t)}$ values (Nutman and Cordani 1993; Martin et al. 1997). By contrast, the Boa Vista granitic gneiss dome is more homogenous and is 3353 Ma old (Nutman and Cordani 1993). Another roughly contemporary bodies such as the Bernarda tonalitic (3386 Ma) and Aracatu trondhjemitic (3325 Ma) massifs (Santos-Pinto et al. 2012) and the Mariana TTG (3259 Ma) suite (Bastos Leal et al. 2003) occur in the central part of the Gavião Block.

According to Martin et al. (1997), the protoliths of the TTG gneiss xenoliths in the Sete Voltas dome were produced by partial melting of an Archean tholeiite, leaving a hornblende garnet residue, whereas their host granodiorite and gray gneiss have geochemical composition different from that of typical TTG and were probably produced by partial melting of an older continental crust. The authors also suggested that partial melting of the older crust took place at depths of 30–45 km. This information, combined with the rocks deformation characteristics and migmatization, was related with an Archean collisional thickening akin to modern type plate tectonics.

Examples of the youngest age group of rocks (3180–3000 Ma, see Table 3.3) occur in the eastern portion of the Gavião Block, such as a granite gneiss (3158 ± 2 Ma) emplaced into the Sete Voltas gneissic dome (Martin et al. 1997), the Lagoa da Macambira granite (3146 ± 24 Ma, Leal et al. 1998), the Lagoa do Morro granodiorite (3184 ± 6 Ma, Nutman and Cordani 1993), and a gneiss of the Mairi Complex (3040 ± 15 Ma, Peucat et al. 2002). Similarly, in the western part of the Gavião Block, the gneissic rocks of the Santa Isabel Complex (Fig. 3.6) may be contemporary with this orogenic stage, as suggested by reconnaissance U–Pb work that yields an upper intercept at ca. 2.95 Ga (with migmatization at ca. 2.75 Ga). However, Rosa (1999) reports U–Pb crystallization age of 3.35 Ga for a gneiss xenolith in the Paleoproterozoic Cara Suja pluton emplaced into the Santa Isabel Complex—in the western edge of the block. Consequently the latter unit may be significantly older, and related to an early accretionary stage of the Gavião Block. The Santa Isabel Complex displays T_{DM} ages of 3.3–3.1 Ga and variable $\varepsilon_{Nd(t)}$ values (−4.7 to +0.3), suggesting juvenile and reworking processes from the Mesoarchean protholiths (Barbosa et al. 2013). Subsequently, episodes of new magma intrusion took place between 2850 and 2520 Ma all over the Gavião Block. The Serra dos Pombos alkaline granitoid (2845 ± 45 Ma; Marinho et al. 1994a, b), the Caraguataí syenitic augen gneiss (2693 ± 5 Ma; Cruz et al. 2012), and the Serra do Eixo alkaline granite gneiss (2693 ± 5 Ma, Santos-Pinto et al. 2012; or 2524 ± 14 to 2656 ± 10 Ma; Bastos Leal et al. 2003) are examples of this assemblage (Table 3.3).

Between Sobradinho and Campo Alegre de Lourdes (northernmost SFC), gneisses and migmatites that are collectively referred to as the Sobradinho Block (Fig. 3.1; Table 3.3) contain rare gabbro-diorite enclaves, on which Dantas et al. (2010) found an old zircon population dated at 3537 ± 8 Ma. The Sm–Nd T_{DM} model ages for the samples yielded ages up to 3.7 Ga, while zircon Hf T_{DM} model ages are between 3.7 and 3.9 Ga (Dantas et al. 2010, 2013). These data provide robust evidence of Eoarchean juvenile components in the block, like the Riacho de Santana gneissic-migmatitic rocks (see above). According to Dantas et al. (2013), the Sobradinho Block may be an independent micro-continent that accreted to the São Francisco paleocontinent during the Paleoproterozoic orogeny. Alternatively, Barbosa et al. (2012) reviewing the geologic-tectonic framework of the northern SFC interpret the Sobradinho Block as the northern portion of the Gavião Block.

Both the Gavião and Serrinha Blocks include a group of rocks dated between 3180 and 3000 Ma (Table 3.3). These ages agree well with U–Pb crystallization ages from orthogneisses of the Campo Belo—Santa Barbara metamorphic Complexes in the southern portion of the SFC (see previous section). However, a similar crustal evolution does not imply initial proximity of the sialic fragments.

3.4.1.2 Greenstone Belts

Relicts of Archean greenstone belt sequences (e.g., Lagoa do Alegre, Mundo Novo, Umburanas, Guajeru, Ibitira-Ubiraçaba, Brumado, including the lower unit of the Contendas-Mirante belt; Table 3.4) are present in both the Gavião and Sobradinho Blocks (Fig. 3.6). Peucat et al. (2002) obtained a zircon U–Pb SHRIMP crystallization age of 3305 ± 9 Ma for a metadacite of the Mundo Novo greenstone belt, showing that this is also one of the most ancient supracrustal sequences in the craton, although few outcrops exhibit well preserved primary features (Fig. 3.7b). Sm–Nd T_{DM} ages for the metadacites vary from 3.6 to 3.4 Ga, with $\varepsilon_{Nd(3.30)}$ values in the range +0.5 to −1.9 (Oliveira et al. 2010). Although few whole rock major and trace element data are available for the volcanic rocks for petrogenetic inferences (e.g., Mascarenhas et al. 1998), the variation of the $\varepsilon_{Nd(t)}$ values suggests that the Mundo Novo rocks may belong to an arc assemblage accreted onto the Gavião Block (Oliveira et al. 2010).

The lower unit of the Contendas-Mirante supracrustal sequence (Table 3.3) contains metabasalt, dacite, BIF, metacherts and marble (Marinho et al. 1994a). TIMS U–Pb zircon dating of a dacite yielded an upper intercept age of 3304 +31/−24 Ma, whereas the Sm–Nd T_{DM} ages are 3.3-3.4 Ga). In addition, BIF samples gave a whole rock Pb–Pb isochron with 3265 ± 51 Ma (Marinho et al. 1994a). This suggests a time correlation between the Contendas-Mirante lower unit and the Mundo Novo greenstone belt, although additional U–Pb provenance studies on the siliciclastic sequences are crucial for testing this hypothesis. However, the upper units of the Contendas-Mirante greenstone belt are Paleoproterozoic in age according to SHRIMP U–Pb work (Nutman et al. 1994).

The Umburanas, Brumado and Ibitira-Ubiraçaba greenstone belts (Fig. 3.6; Table 3.4) are similar and contain metakomatiites and metabasalts at the base (Fig. 3.7b), followed up section by felsic metavolcanics and metasedimentary rocks. Detrital zircons recovered from one Ibitira-Ubiraçaba schist collected close to Caetité town indicated ages ranging between 3.5–2.5 and 2.0–2.1 Ga (prevailing metamorphic event), except one grain (4.1 Ga)—the oldest zircon so far found in the SFC (Paquette et al. 2015). According to these authors this indicates that Hadean-aged materials incorporated to the SFC, in agreement with published Sm–Nd T_{DM} ages (see below). The

Table 3.4 Geologic and geochronology characteristics of greenstone belts in the northern SFC

Greenstone belts	Distinguished geologic features	Age (Ma)	Occurrence/tectonic distribution	References
Mundo Novo	Low grade metamorphic pillow basalts, intermediate lavas, chemical and clastic sedimentary rocks	Metadacite (zircon SHRIMP U–Pb age: 3305 ± 9)	Allochthonous supracrustal sequence accreted onto grey gneisses. Crustal compression tectonically related with the Paleoproterozoic Itabuna–Salvador–Curaçá belt	1
Lagoa do Alegre	Low- to medium grade metamorphic mafic and ultramafic (komatiite) rocks, chemical and clastic sedimentary rocks	Intrusive granite minimum age: 3300	Dismembered tectonic slivers within Archean gneiss-migmatite basement	2, 3
Guajeru	Low- to medium grade metamorphic mafic and ultramafic rocks, chemical and clastic sedimentary rocks	Intrusive alkaline granites (zircon Pb evaporation minimum age: 2649 ± 15 to 2670 ± 15)	Slievers of greenstone associations intermingled with basement rocks, syntectonically intruded by 3.1 Ga TTG rocks	3, 4
Umburanas, Brumado, Ibitira-Ubiraçaba	Low- to medium grade metamorphic supracrustal sequences: ultramafic to felsic metavolcanics, chemical (BIF) and clastic sediments	Meta-andesite (Umburanas greenstone belt): U–Pb age of 2744 ± 15. Minimum age of 2693 ± 5	Greenstone associations intermingled with basement rocks, intruded by TTG suites	3, 5
Boquira	Meta-ultramafics, metabasalts, chemical and clastic sediments	Galena (Pb–Pb age of 2.5–2.7 Ga)	Greenstone association with basement gneisses and migmatites	3

References: (1) Peucat et al. (2002); (2) Angelim (1997); (3) Cunha et al. (2012); (4) Lopes (2002); (5) Bastos Leal et al. (2003). See also Table 3.3.

Umburanas greenstone belt was partially studied by means of radiometric ages. A meta-andesite from the intermediate unit yielded zircon Pb evaporation age of 2744 ± 15 Ma (Bastos Leal et al. 2003). No age determinations are available for the basaltic-komatiitic lower unit or for the carbonate upper unit of the Umburanas greenstone belt. It is, however, definitely older than 2693 ± 5 Ma, which is the age of the Serra do Eixo intrusive granite (Santos-Pinto et al. 2012). Similar field relationships were found in the Guajeru greenstone belt, where alkaline granitoids intrusive into supracrustal rocks of the belt yielded zircon Pb evaporation ages between 2649 ± 15 and 2670 ± 15 Ma (Barbosa et al. 2012).

Other relicts of greenstone belts in the Gavião Block have ages poorly constrained or no age data. For instance, the Boquira greenstone belt (Table 3.4) is composed of ultrabasic rocks (metakomatiites?), metabasalts, and clastic and chemical metasedimentary rocks. Pb–Pb analyses for galena samples from the Boquira mine yielded model ages in the time interval 2.7–2.5 Ga, interpreted as the minimum age of the Pb and Zn sulfides (Cunha et al. 2012). These authors report a list of the main exposures of greenstone belts in the Gavião Block. Finally, in the Sobradinho Block, the Lagoa do Alegre greenstone belt comprises a lower volcanic-sedimentary sequence and an upper metasedimentary sequence. According to Angelim (1997) granitoid intrusions dated at 3300 Ma constrain a Mesoarchean age for the metavolcanic-sedimentary association.

3.4.2 The Serrinha Block

The Serrinha is the smallest Mesoarchean block in the northern SFC (Fig. 3.8), but the wealth of field relationships coupled with geochronological and geochemical data makes it one of the best-known areas of the craton. The Serrinha Block occurs as an elongated N–S segment up to 100 km wide, limited to the west and to the south by tectonic contacts with the Paleoproterozoic Itabuna–Salvador–Curaçá belt. Two migmatite-gneiss complexes (Santa Luz and Uauá) can be distinguished in this block, intruded by mafic dikes and mafic–ultramafic complexes (see below). The country rocks were metamorphosed under amphibolite to granulite facies conditions and lie in tectonic contact with Paleoproterozoic rocks of the Rio Capim and Rio Itapicuru greenstone belts (Schrank and Silva 1993; Oliveira et al. 2010 and references therein). Syn- to late-tectonic granitoid plutons are emplaced into these greenstone belts, where the domic structures are related with the Paleoproterozoic orogeny (Mello et al. 2006).

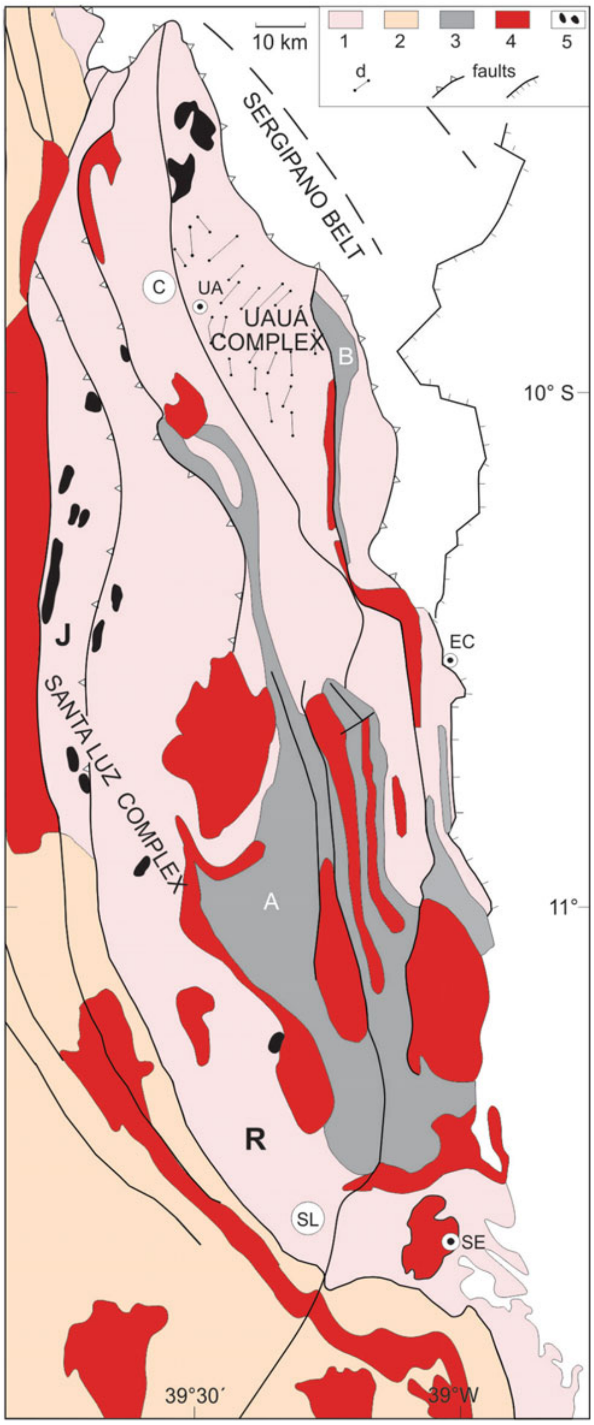

Fig. 3.8 Geologic sketch of the Mesoarchean Serrinha Block (adapted from Oliveira et al. 2010; Barbosa et al. 2012). *1* Archean substratum partly reworked in Paleoproterozoic times: C = Caldeirão belt; SL = Santa Luz complex with the Jacurici (J) and Retirolândia (R) domains; Uauá Complex intruded by Neoarchean mafic dikes. *2* Caraíba complex. *3* Paleoproterozoic greenstone belts: Itapicuru (A) and Rio Capim (B). *4* Paleoproterozoic granites. *5* Mafic-ultramafic complexes. Towns: EC = Euclides da Cunha; SE = Serrinha; UA = Uauá. See Table 3.3 and text for details

The Santa Luz Complex (Fig. 3.8; Table 3.3) contains Mesoarchean (3085–2983 Ma) migmatites, banded gneisses, TTG orthogneisses, mafic–ultramafic complexes, and mafic dikes (Oliveira et al. 2010). The banded gneiss unit is the end product of deformation of migmatites and mafic dikes during the accretion of the Paleoproterozoic Rio Itapicuru greenstone belt onto the Archean basement (Oliveira 2011). Paleoproterozoic plutons related to the Itabuna–Salvador–Curaçá belt intrude both the Archean substratum and the Paleoproterozoic supracrustal units. One of those (Quijinge trondhjemite pluton) yielded U–Pb age determinations in inherited zircons of 3314 and 3620 Ma (Rios et al. 2008). Other plutons like the Ambrósio granitic dome inside the Rio Itapicuru greenstone belt hosts migmatitic gneiss enclaves as old as 3.1 Ga (Mello et al. 2006). This suggests that Paleoarchean to Mesoarchean material formed the precursor crust of the Serrinha Block. From a geochronological point of view the Santa Luz Complex can be divided into two domains of grey gneisses, i.e. the Retirolândia (ca. 3085 Ma) and the younger Jacurici domain (ca. 2980 Ma) (Oliveira et al. 2010) (Fig. 3.8). Both domains are composed of TTG suites respectively with Sm–Nd T_{DM} model ages in the time intervals 3.1–3.2 Ga and 2.9–3.1 Ga. The $\varepsilon_{Nd(t)}$ values vary from +1.1 to zero and +2.7 to −0.8, respectively (Oliveira et al. 2010), indicating a predominant juvenile origin.

Conversely, the Uauá Complex (Fig. 3.8; Table 3.3), which may be an allochthonous block (Oliveira 2011), is bordered to the west by the Archean-Paleoproterozoic Caldeirão belt and to the east by the Paleoproterozoic Rio Capim greenstone belt (Oliveira et al. 2011, 2013). The Uauá basement consists mostly of NW-trending, ancient banded gneisses (of unknown age) intruded by Mesoarchean layered anorthosite, peridotite and diorite complexes, metamorphic mafic dikes, and tonalite-granodiorite bodies. Neoarchean non-metamorphic norite-tholeiite dikes crosscut in places the country rocks (Oliveira 2011; Oliveira et al. 2013, and references therein). Except the Neoarchean dikes (norite 2726 Ma and tholeiite 2623 Ma; Oliveira et al. 2013), much of the basement rocks underwent granulite facies metamorphism and were later retrogressed to amphibolite grade.

The granulite-facies felsic igneous bodies with intercalated garnet-bearing mafic granulites are strongly foliated, often with horizontal, or south-dipping low-angle foliation. They show stretching lineations and asymmetric folds indicative of having been thrust northward (Oliveira et al. 2013 and references therein). The banded gneisses, 3.0 Ga old, show slightly negative to positive $\varepsilon_{Nd(3.0Ga)}$ values and major and trace element geochemical characteristics akin to a subduction zone setting (Oliveira et al. 2010). As such, these rocks potentially represent exhumed tectonic slices of the roots of a Mesoarchaean continental arc (Oliveira et al. 2010), as suggested by the widespread U–Pb ages. Cordani et al. (1999) obtained ages between 3120 and 3130 Ma for the Capim tonalite, whereas Oliveira et al. (2010) reported on felsic igneous bodies with ages between 3072 and 2991 Ma. The younger tholeiite dike swarm (2623 Ma) that crosscuts the Uauá crust may represent a failed arm of a Neoarchean rift system (Oliveira 2011; Oliveira et al. 2013).

The Caldeirão belt (Caraíba Complex), bounded to the east by the Uauá Complex (Fig. 3.8), comprises a 10-km wide sheared sequence of steeply dipping quartzites, sillimanite-cordierite-garnet gneisses, granodioritic orthogneisses, mafic rocks and migmatites, all metamorphosed under amphibolite to granulite facies conditions. SHRIMP U–Pb age indicates a 3150 Ma age for one orthogneiss and 2076–2040 Ma dating for the regional deformation and metamorphism (Oliveira et al. 2002). Deformation of the Caldeirão belt took place during northward lateral extrusion of the Uauá Block in the Paleoproterozoic (Oliveira et al. 2013)—see Table 3.3.

Two major Archean mafic-ultramafic intrusions occur in the Serrinha Block: the Lagoa da Vaca anorthosite complex and the Pedras Pretas mafic-ultramafic complex. The first one (Paixão and Oliveira 1998) crops out close to a major ductile shear zone that separates the Uauá banded gneisses from the Caldeirão migmatite-quartzite-orthogneiss belt (Fig. 3.8). The complex makes up a metamorphosed layered igneous body composed of plagioclase and amphibole-rich bands. A whole-rock Pb–Pb isochron yielded the age of 3160 ± 65 Ma, suggesting that the anorthosite is the oldest ever found in the SFC. This isochron presents a model μ_1 Pb value of 8.8 ± 0.6, compatible with its derivation from the sub-continental lithospheric mantle or from the depleted mantle, in both cases followed by crustal contamination. Therefore the anorthosite emplacement is likely to have occurred in a continental setting, most likely similar to a present-day passive continental margin (Paixão and Oliveira 1998). The Pedras Pretas mafic-ultramafic complex is crosscut by mafic dikes with a minimum Neoarchean age (Oliveira et al. 2012). It comprises a small body of chromitite-rich serpentinite interleaved with banded gneisses of the Santa Luz complex. Further geochronological and isotopic studies are needed to constrain the emplacement age and genesis of the mafic-ultramafic complex.

3.4.3 The Jequié Block

This block (Fig. 3.1b; Table 3.3) occurs to the SE of the Contendas-Jacobina Lineament, stretching eastwards almost to the Atlantic coast. It contains several north-south trending belts composed of Archean high-grade rocks, separated by faults, and showing strong deformation and emplacement of granitic material tectonically related to the Paleoproterozoic orogeny (e.g., Nutman and Cordani 1993).

According to Barbosa et al. (2012) the Jequié Block consists of calc-alkaline plutonic rocks mainly represented by gneisses and acid granulites. On the northeastern portion, gabbro-anorthosite bodies dominate, whereas on the eastern portion, close to the Itabuna–Salvador–Curaça orogen, Barbosa (1990 and references therein) mapped amphibolite facies banded gneisses with amphibolite and quartz-feldspar bands. Charnockitic granulites as well as granulite facies supracrustal rocks (i.e., garnet- and cordierite-bearing charnockites of sedimentary origin), on the other hand, are conspicuous over the northern portion of the block. They are believed to be intracratonic basin deposits. Inhomogeneous ortho-, and para-derived granulites as well as enderbitic to charnockitic rocks are also present in the western and central portion of the block, whose protholiths preserve Archean ages, though the tectonic-metamorphic history relates to the nearby Paleoproterozoic geodynamics. As a matter of fact, the Jequié Block has been considered to be one of the Archean blocks that were involved in the collision with the Serrinha and Gavião Blocks during the Paleoproterozoic orogeny (e.g., Teixeira et al. 2000 and references therein). Therefore, the main structures of the block are thrust faults that set the block's boundaries; all of them are related to the Paleoproterozoic orogeny.

Zircon SHRIMP U–Pb ages for charnockitic granulites of the Jequié Block cluster around 2.7 Ga for the protolith ages, and between 2.06 and 2.05 Ga for the high-grade metamorphism (Silva et al. 2002; Barbosa and Sabaté 2004). For instance, Silva et al. (2002) reported a 2715 ± 29 Ma protolith age for one charnockitic granulite with high-grade metamorphic overprint at 2047 ± 14 Ma, whereas other sample yielded younger protolith age (2473 ± 5 Ma) and metamorphism at 2061 ± 6 Ma. Barbosa and Sabaté (2004) reported a SHRIMP zircon age of 2689 ± 7 Ma for an enderbitic granulite in the Mutuipe area. Sm–Nd T_{DM} model ages for the Jequié rocks fall in the time span 3.3–2.9 Ga (Marinho et al. 1994a, b; Barbosa and Sabaté 2004), and the negative $\varepsilon_{Nd(t)}$ values suggest that the plutonism formed through reworking of Mesoarchean crust. This model agrees well with the crustal evolution of the southern portion of the SFC, as envisaged here.

Finally, the Rio do Jacaré sill is approximately 900 m thick and 70 km long body sandwiched between the Jequié Block and the Contendas-Mirante supracrustal sequence (Fig. 3.8). It varies in composition from gabbro to leucogabbro with minor pyroxenite, and hosts Brazil's largest vanadium deposit (Brito 2000). Marinho et al. (1994a, b) dated the sill at 2474 ± 72 Ma by means of a Pb–Pb whole rock isochron, but citation of unpublished data in Leite and Marinho (2012) indicate zircon LA-ICP-MS and Pb evaporation ages respectively of ca. 2630 and 2650 Ma.

3.4.4 The Basement of the Itabuna–Salvador–Curaçá Belt

Remnants of Archean rocks are also found within high-grade orthogneisses of the Paleoproterozoic Itabuna–Salvador–Curaçá belt (e.g., Oliveira et al. 2010 and references therein) (Fig. 3.1b; Table 3.3). The orogen formed by accretion of ca. 2.19 Ga arc-like rocks onto the Jequié Block located to the south (Peucat et al. 2011 and references therein). Crustal evolution included Paleoproterozoic reworking of the arc rocks and their Jequié Archean substratum in the south, as well as the Neoarchean continental arc crust in the north (Caraiba Complex; see Fig. 3.8), and final intrusion of syn- to post-tectonic igneous bodies (Barbosa et al. 2008; Oliveira et al. 2010). Barbosa and Barbosa (this book) presents a more detailed description of the Paleoproterozoic geologic-tectonic setting.

In the southern portion of the Paleoproterozoic Itabuna–Salvador–Curaçá belt, Silva et al. (2002) report Neoarchean ages on scattered rocks such as on charnockitic granulites with zircon SHRIMP U–Pb ages of 2719 ± 10 Ma at the Pernambuco hill in Ilhéus, 2799 ± 18 Ma on roadside to Ipiaú, 2847 ± 7 Ma at the Coaraci quarry, and 2715 ± 29 Ma at Jitauna, road Ipiaú to Jequié. Most of the zircon grains dated by Silva et al. (2002) show metamorphic rims with ages between 2078 and 2047 Ma. Peucat et al. (2011) found a slightly younger age of 2675 ± 11 Ma on zircon cores from an enderbitic granulite west of Itapitanga with metamorphic rims at 2080 ± 21 Ma, as well as arc-related intrusions ca. 2.19 Ga old.

In the northern portion of the orogen (Fig. 3.8), the 2634–2695 Ma Caraíba charnockitic granulites close to São José do Jacuípe (see previous section) also indicated Paleoproterozoic reworking on zircon metamorphic rims, which dated mostly between 2082 and 2072 Ma (Silva et al. 1997). The latter ages match with the time interval of high-grade metamorphism and extremely reworking of Archean protoliths along the orogen, as well as the intrusion of syn- to late tectonic granitic bodies (Oliveira et al. 2010; Barbosa et al. 2008). Neoarchean remnants younger than those at south are also present, as indicated by SHRIMP ages on zircon cores from 2574 Ma Caraíba charnockitic granulite (Oliveira et al. 2010). In a similar way, the Neoarchean protoliths of the Jequié Block exhibit extensive recrystallization of zircon rims due to Paleoproterozoic high-grade metamorphism (see previous section).

Finally, two major Archean mafic-ultramafic complexes occur in the northern extension of the Itabuna–Salvador–Curaçá belt, namely the Caraíba norite-pyroxenite and the São José do Jacuípe leucogabbro complexes. Both complexes are similar in age, i.e. 2580 ± 10 Ma (zircon U–Pb SHRIMP) for Caraíba and 2583 + 8 Ma (zircon U–Pb SHRIMP) for São José do Jacuípe (Oliveira et al. 2010). The former hosts a copper sulphide deposit and occurs as deformed dikes and large bodies intruded into migmatite gneisses (Oliveira et al. 2004). Conversely, the São José do Jacuípe complex is non-mineralized and occurs as dismembered small bodies of layered anorthosite-gabbro-pyroxenite in syn-, to late-tectonic granites (Piaia 2011). According to Oliveira et al. (2010) and Piaia (2011), the two mafic-ultramafic complexes may be part of the roots of a Neoarchean continental arc represented by the ca. 2.65–2.56 Ga tonalite-granodiorite protoliths of the Paleoproterozoic Caraiba Complex. As a whole, this scenario allows a correlation with the Neoarchean collisional event hypothesized here for the southern portion of the SFC.

3.5 Concluding Remarks

The SFC, like its African counterpart (the West Congo Craton), results from accretion of distinct Archean fragments essentially composed of medium- to high-grade gneisses including TTG suites, and granite-greenstone associations. This polycyclic substratum was assembled during late Neoarchean times under high-grade metamorphic conditions, and intruded by late tectonic K-rich granites, mafic-ultramafic suites, and mafic dikes.

The new and compiled data indicate that the Sobradinho, Gavião, Serrinha and Jequié Blocks in conjunction with the southernmost basement segment of the SFC (Fig. 3.1) show diachronic evolution from Paleo- to Neoarchean times by means of juvenile accretion/differentiation of continental crust, coupled with partial melting events of earlier-formed material. This tectonic evolution is coherent with the geochemical and U–Pb isotopic data on both igneous zircon cores and their metamorphic rims of igneous and metaigneous rocks, as well as with detrital zircon ages of supracrustal sequences (e.g., Ibitira-Ibiraçaba sequence; see previous section). We interpret these results as a robust evidence of multiple pulses of TTG plutonism in genetic association with greenstone belts, as in modern oceanic arcs and active continental margins. In particular, both the TTG suites and granitoid rocks, varying in time and extent, are time markers of the progressive thickening and differentiation of the continental crust through time, leading to tectonic stabilization of the landmasses at the end of the Archean.

Figure 3.9 presents the U–Pb zircon crystallization ages and Sm–Nd T_{DM} whole rock model ages for Archean country rocks of the SFC, based on published data. Considering that Sm–Nd T_{DM} model ages are usually ca. 200 m.y. older than the corresponding U–Pb age for a given rock, the observed peaks (coupling both methods) can be taken as reasonable estimates of the bulk Archean accretion/crustal differentiation

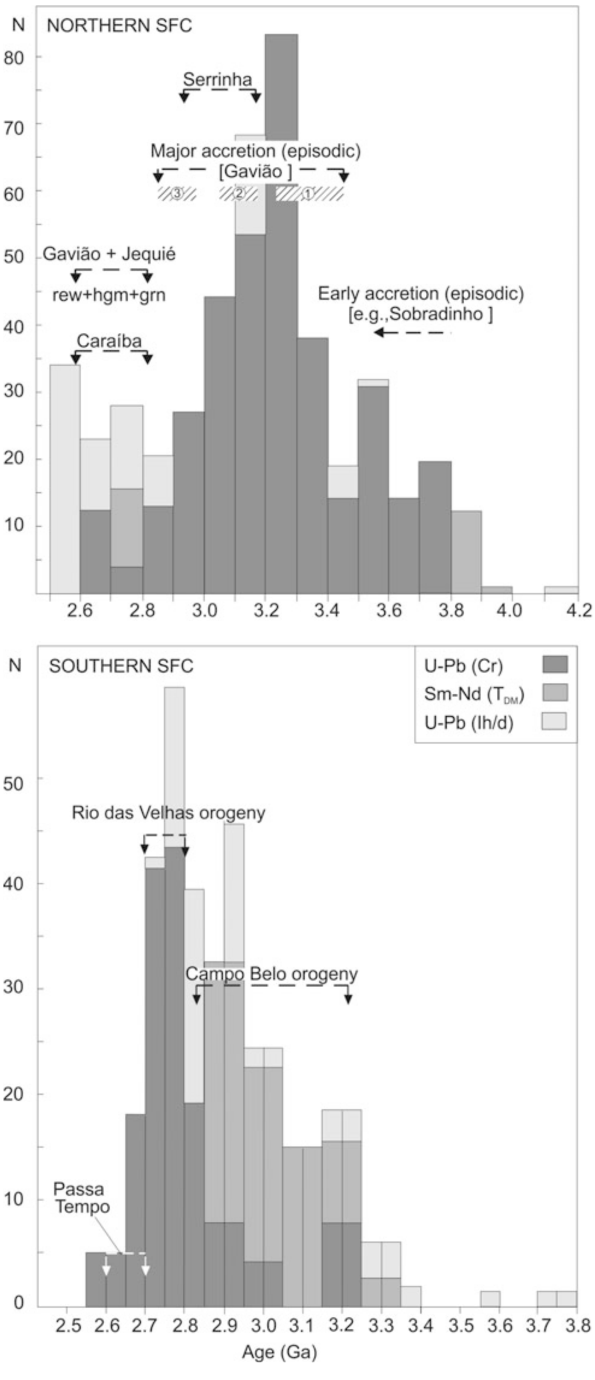

Fig. 3.9 Geochronological histogram, showing the main Archean accretion and recycling episodes in both the northern and southern parts of the Craton, given by peaks of zircon U–Pb crystallization ages and Sm–Nd T_{DM} model ages (whole rocks). Keys: rew (crustal reworking), hgm (high-grade metamorphism), grn (granite-genesis); Cr (crystallization age), Ih/d (inherited or detrital grains ages). Note that the histograms have different scale. See text for details

events. However, we are aware that there might be a bias due to the heterogenous number of U–Pb ages available for the southern and northern parts of the SFC. Nevertheless, the resulting geochronological scenario, which is roughly similar for both portions of the craton, is consistent with a protracted Archean history for the proto-SFC, starting in the Hadean time, and highlighted by the peculiar tectonic-metamorphic histories of the basement rocks and coeval greenstone belts. The possible physical link among the primitive fragments was obliterated by crustal remobilization, high-grade metamorphism, shortening processes, and granite emplacement during subsequent collisions of the intervening Paleoproterozoic belts (Teixeira et al. 2015). This complexity hampers a correlation among the Archean units.

Scattered zircon U–Pb crystallization and inherited ages > 3.6 Ga on Fig. 3.9 refer to the oldest Paleoarchean components in South America, such as a Hadean xenocryst (4.1 Ga) in the Ibitira-Ibiraçaba schist, and igneous zircons from Riacho de Santana gneiss (3.6 Ga) in the Gavião block (Sm–Nd T_{DM} age of 3.9 Ga). A gabbro-diorite enclave in gneiss (3.5 Ga old) of the Sobradinho block yields Sm–Nd T_{DM} model age of 3.7 Ga and zircon Hf T_{DM} model ages between 3.7 and 3.9 Ga. Moreover, the Neoarchean Rio das Velhas greenstone belt in the southern SFC similarly contains detrital zircons as old as 3.8 Ga. Therefore there is isotopic evidence for Hadean differentiated crust incorporated to the SFC sialic core.

The ages older than 3.6 Ga on Fig. 3.9 suggest that Paleoarchean crustal growth was episodic. For instance, inherited age clusters in detrital zircons in the Proterozoic Tombador cover (Guadagnin et al. 2015) and in the northern SFC suggest that sediment accumulation accompanied by sediment recycling has operated since Paleoarchean times. This concurs with models of accretion and recycling of the early continental crust, via subduction due to vigorous and hotter thermodynamic mantle conditions (e.g., Rey and Coltice 2008 and references therein).

Major Mesoarchean accretion is apparent between 3.5–3.3 and 3.2–2.9 Ga (Fig. 3.9), according to the age peaks (U–Pb + Sm–Nd T_{DM}) for both the northern (episodes 2 and 3; Gavião Block) and southern portions of the SFC (Campo Belo orogeny). Specifically, the orthogneisses and migmatites of the Serrinha Block (northern portion) and the Campo Belo and Santa Bárbara Complexes (southern portion; Campo Belo orogeny) accreted between 3.2 and 2.9 Ga (Fig. 3.9). Taking into account the entire ancient core of the SFC, these data indicate again vigorous continental growth at this time.

The Rio das Velhas orogeny (2790–2750 and 2730–2700 Ma; Fig. 3.9) produced gneissic-granitic complexes and coeval granite-greenstone associations in an active continental margin setting. The final phase of this orogeny also led to pervasive crustal remobilization of older rocks and high-grade metamorphism representing a late collision stage (e.g., Passa Tempo Complex; Fig. 3.9) of the Archean fragments. Crustal derived granite plutons dated from ca 2.65 to 2.55 Ga led to tectonic stability of the continental crust. Such a model compares well with the geochronological evolution (2.70–2.55 Ga) of the Jequié Block as well as with that of the Caraíba Complex (Fig. 3.9), which are the reflection of similar high-grade metamorphism, granite intrusion and crustal reworking of Archean protoliths. Collectively, this evidence points to the important role of Neoarchean assembly of older polycyclic rocks. Whether the Neoarchean Caraíba Complex (basement of the Paleoproterozoic orogen) represents or not an extension of the Jequié block deeply reworked by the Paleoproterozoic orogeny is still uncertain.

Limited structural evidence (e.g., flat foliation with sub-horizontal sheath folds) in local exposures of the Archean crust, such as in the Aracatu region (Gavião block), Ipiaú band (Jequié Block) and Passa Tempo Complex, favors the model of Neoarchean contractional tectonics, as also suggested by the isotopic evidence. However, vertical tectonics has been reported in places of the Jequié Block (Teixeira et al. 2000 and references therein). In any case, these models are dependent on further robust geochronology and isotopic-geochemical evidence.

It has been of widely acceptance that some kind of plate tectonics was in operation since early Archean times (e.g., Condie 2007; Martin et al. 2010; Shirey and Richardson 2011; Dhuime et al. 2012). From the geochemical point of view, the chondrite-normalised La/Yb versus Yb plot for Archean rocks, among other correlative diagrams, helps to constrain the operating tectonic processes, as shown on Fig. 3.10. In this diagram, the trace element data for selected rock units in both the northern and southern cratonic areas are plotted. Most gray gneisses older than 3.0 Ga of the Gavião Block, the ca. 3.0 Ga Santa Luz Complex in the Serrinha Block, and the ca. 2.7 Ga Passa Tempo Complex (southern SFC) show chemistry compatible with TTG suites, enhanced by strong fractionation of light from heavy REE patterns and minor or absent Eu anomalies (Teixeira et al. 2010). Therefore, these rocks may have been originated by partial melting of a garnet-bearing mafic source at great depths (e.g., Rapp et al. 1991). Moreover, some REE patterns for the 3.4 Ga Mariana dome (northern SFC) display little fractionation of light from heavy REEs and pronounced negative Eu anomalies (Teixeira et al. 2010). This indicates that plagioclase fractionation played a significant role. In other words, this may be alternatively explained by partial melting at the base of an oceanic plateau, such as what was recently postulated for the Earth's earliest evolved crust (e.g., Reimink et al. 2014). However, in the case of the SFC rocks, such interpretation still depends on further detailed geochemical and isotopic studies plus re-evaluation of previous published data. On the other hand, the 3.0 Ga rocks of the Uauá Complex (Serrinha Block), the 2.7 Ga gneisses of the Jequié Block, and the granite gneisses of the Meso- and Neoarchean Campo Belo, Bonfim, and Belo Horizonte Complexes (southern SFC) show geochemical characteristics very much like the calc-alkaline series. Therefore, there is robust evidence for origin of these units in tectonic settings similar to modern subduction zones. For instance, the younger Neoarchean alkaline granites in the Gavião Block may have had the TTG terrains as their crustal sources. After Neoarchean tectonic stability and ultimate thickness of the continental crust, an emplacement of mafic ultramafic suites and mafic dikes occurred, such as those emplaced into the Uauá Block and in the Passa Tempo complex.

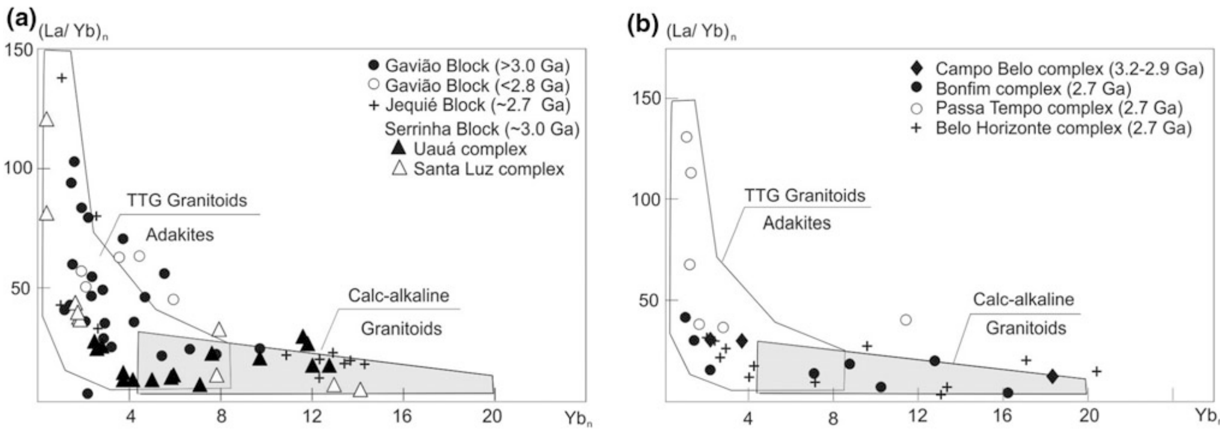

Fig. 3.10 Chondrite-normalised La/Yb versus Yb, showing the geochemical characteristics of Archean granitoids and *gray* gneisses of the northern (**a**) and southern (**b**) parts of the craton (see Fig. 3.1)

Figure 3.11 presents a paleotectonic cartoon for the SFC based on geologic and geochronologic information that highlights a mosaic of individual Archean segments encircled by Paleoproterozoic orogenic domains. For instance, previously published gravimetric and aeromagnetic interpretations dealing with garnet bearing rocks over the Serrinha Block indicated variations of the pressure parameters. They are consistent with the idea of a thicker lithospheric keel with thinner edges, due to Paleoproterozoic reworking during the Itabuna–Salvador–Curaçá orogen (Pereira and Fuck 2005). As a corollary, we can similarly think about a thick, mantle keel in the Gavião Block, given the long-lived production of continental crust since Paleoarchean times, thus providing the proto-craton's stability and consequently the rheological conditions for emplacement of huge amount of mafic-ultramafic magmas in the late Neoarchean.

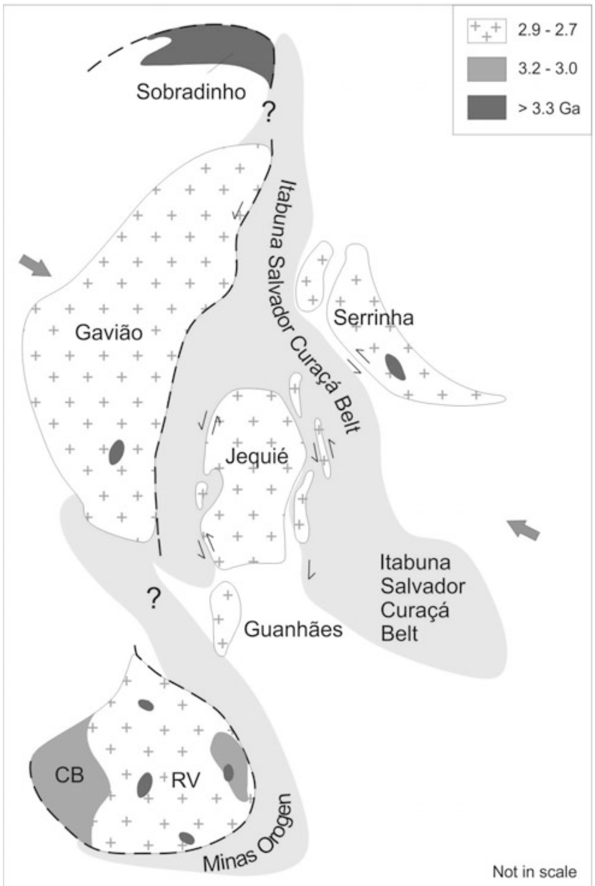

Fig. 3.11 Cartoon of the paleotectonic framework (São Francisco proto-craton) distinguished by individual Archean continental fragments/blocks, and the adjoining Paleoproterozoic collage, given by the Minas orogen and the coeval Itabuna–Salvador–Curaçá belt. Keys: CB (Campo Belo orogeny), RV (Rio das Velhas orogeny). (Adapted from Alkmim and Noce, 2006). See text for details

Additional geophysical data (Pereira and Fuck 2005) in the southern SFC similarly indicate the transition from thicker lithosphere (typical of Archean terrains, as supported by the radiometric ages) to thinned lithosphere of the Neoproterozoic marginal belt nearby the Piumhi greenstone belt (Table 3.2; Fig. 3.2). In the African counterpart, Tadjou et al. (2009) report a similar picture, based on interpretation of gravity-based geophysical study involving the Congo Craton and the allochtonous Pan-African belt in Cameroon; whereas the ancient crust of the Congo craton is relatively thick, consisting mainly of low-density rocks, most Pan-African belt rocks are relatively denser.

Finally, from a geodynamic perspective, the integrated data suggest that juvenile accretion played a fundamental role from Paleoarchean to Neoarchean times. The eventual Neoarchean assembly of distinct blocks (e.g., Gavião, Jequié) and/or sialic fragments (e.g., Bonfim and Belo Horizonte Complexes; Quadrilátero Ferrífero) took place diachronically between ca. 2.80 and 2.70 Ga, including high-K plutonism, essentially by means of plate tectonics processes. The Sobradinho and the Serrinha Blocks may represent allochthonous blocks due to their peculiar age records without Neoarchean imprint, although this hypothesis must be tested by robust geochronology and coupled isotopic and geochemical studies.

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