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Reconstruction of Precambrian terranes of Northeastern Brazil along Cambrian strike-slip faults: a new model of geodynamic evolution and gold metallogeny in the State of Bahia

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Abstract

The Precambrian basement of Northeastern Brazil is the product of Rhyacian block convergence. The main deformation and intrusion of crustal granitoids occurred between 2.15 and 1.8 Ga ago. This large area has been subjected to long-lasting and rather uniform stresses during the Cambrian period. Gold provinces in Bahia represent metallogenetic products of distinct tectonothermal events. Gold mineralization took place during the Paleoproterozoic collision and the Cambrian convergence, respectively, accompanied by heat flow, crustal deformation, and granite intrusion. The tectonic framework of the region was reconstructed at ca. 700 Ma ago, considering the hypothesis of wrench-fault tectonics. The new hypothesis provides geological evidence and metallogenic constraints that make further investigation necessary, with reference to well-established São Francisco Craton concept and its peripheral fold belts.

KEYWORDS: Terrane reconstruction; Rhyacian collision; Cambrian strike-slip faults; Gold metallogeny; Bahia; Brazil.

INTRODUCTION

The main objective of this article is to discuss current information of the close connection between thermotectonic processes, which occurred from the Archean to the Paleozoic, and gold mineralization in the State of Bahia, Brazil. Support is obtained through the theories of plate tectonics and paleocontinent evolution.

The South American platform was defined as the stable continental portion of the South American plate, which was not affected by Phanerozoic orogenies. Its basement consists of Precambrian terranes, which were assembled and re-arranged during major orogenic events from the Paleoproterozoic to the Neoproterozoic (Almeida *et al.* 2000). Most of the crustal components of the South American platform, *e.g.* the Guyana, Central Amazonian, Ventuari-Tapajós, Rio Negro-Juruena, Rondônia-San Ignácio, Sunsás, Rio de la Plata and São Francisco blocks, were part of the Atlantica paleocontinent that grew at a faster rate during collision-related arc magmatism and subsequent mantle upwelling in the interval from 2.1 to 1.8 Ga ago (Teixeira *et al.* 2007).

The São Francisco Craton and Borborema Province are two large geotectonic units of the South American platform situated near the Atlantic coastline. Although the origins of these two continental landmasses have traditionally been interpreted as unrelated (*e.g.*, Cordani *et al.* 2000), the pieces of evidence discussed herein lead to a new hypothesis for connected geotectonic and metallogenic evolution. (Fig. 1).

In order to develop and investigate the present hypothesis, a review of the Paleoproterozoic tectonic processes involved in the collision and amalgamation of South American terranes is taken into consideration, including (i) present-day distribution of iron deposits and occurrences that originally belonged to a single Archean basin; (ii) distribution of gold provinces, which represent the metallogenic products of distinct tectonothermal phases, and (iii) important crustal deformation produced by Cambrian strike-slip faults that affected the eastern margin of South America during the West Gondwana assembling. Thus, the paper reviews geotectonic models for the São Francisco Craton and Borborema Province and proposes a new geodynamic model.

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CURRENT GEOTECTONIC MODEL

São Francisco Craton

The configuration of São Francisco Craton was established by Almeida (1977) and modified by Alkmim (2004). It includes

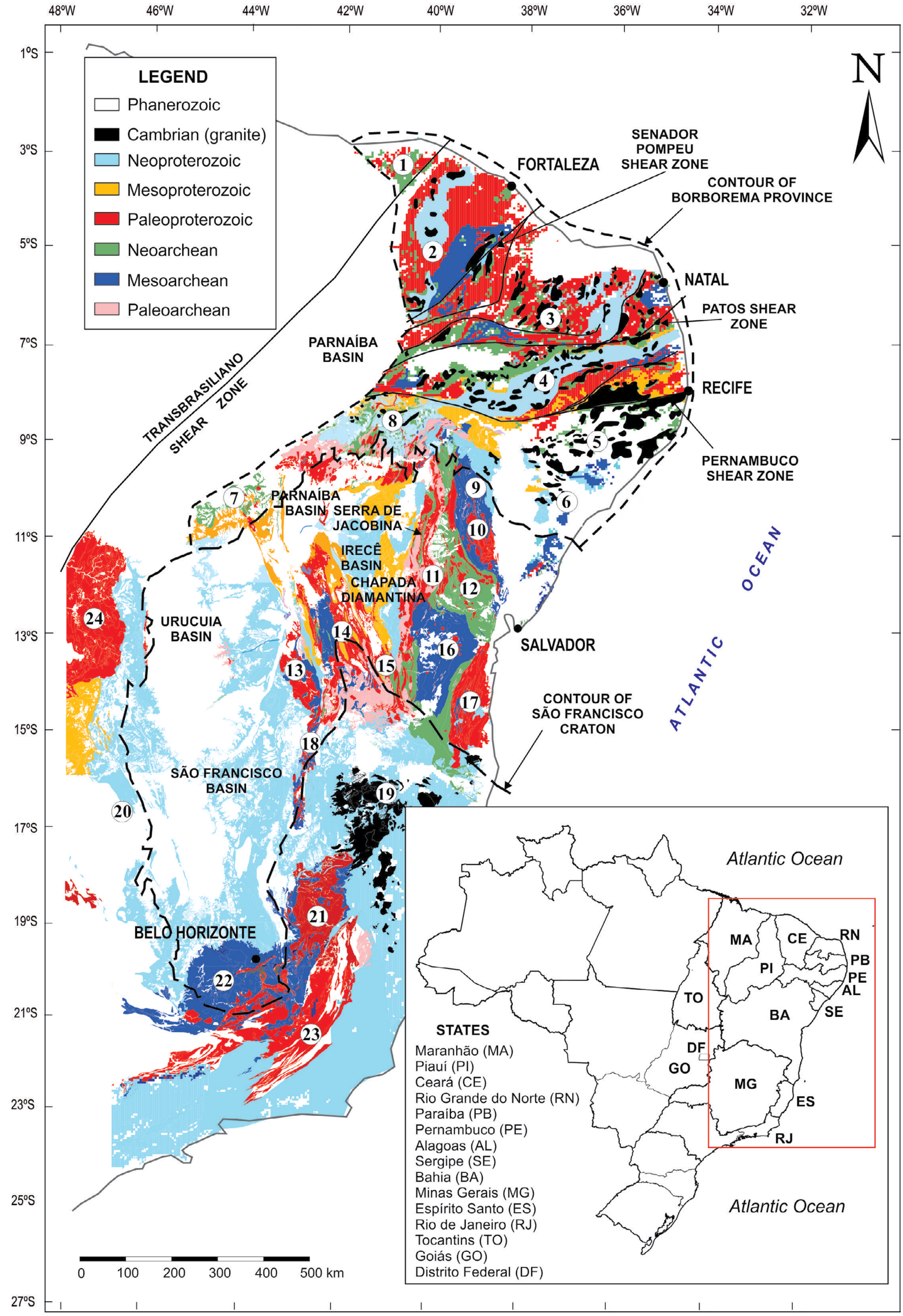


Figure 1. Geological map of the Eastern sector of Brazil after Schobbenhaus *et al.* (2004). Contour of the São Francisco Craton after Almeida (1977), modified by Alkmim (2004). The numbered circles refer to the following lithotectonic units: (1) Middle Coreaú Domain; (2) Santa Quitéria Domain; (3) Northern Domain; (4) Transversal Domain; (5) Southern Domain; (6) Sergipano Fold Belt; (7) Formosa do Rio Preto Fold Belt; (8) Riacho do Pontal Fold Belt; (9) Uauá Block; (10) Serrinha Block; (11) Mairi Block; (12) Salvador-Curaçá Mobile Belt; (13) Guanambi-Correntina Block; (14) Paramirim Aulacogen; (15) Gavião Block; (16) Jequié Block; (17) Itabuna Mobile Belt; (18) Espinhaço Aulacogen; (19) Araçuaí Fold Belt; (20) Brasília Fold Belt; (21) Guanhães Complex; (22) Divinópolis Complex; (23) Juiz de Fora Complex; (24) Almas-Cavalcante Complex.

the largest parts of Bahia and Minas Gerais states, which is limited by peripheral fold belts of Neoproterozoic age (Fig. 1). Ten Archean crustal blocks are identified in the cratonic basement, namely Gavião, Jequié, Serrinha, Uauá, Mairi, Guanambi-Correntina, Paramirim, Guanhães, Divinópolis, and Juiz de Fora blocks (Alkmim *et al*. 1993, Barbosa & Sabaté 2004). The São Francisco Craton assemblage in Bahia is attributed to a major collision event involving Gavião, Jequié, and Serrinha blocks. Geochronological constraints indicate that the peak of regional metamorphism resulting from crustal thickening has been associated with a collision that took place in the Orosirian, *ca*. 2,000 Ma ago. Exhumed roots of this Paleoproterozoic orogenic system make up the granulite-granitoid Salvador-Curaçá and Itabuna belts (Barbosa & Sabaté 2004). Alternatively, the collision system at the Quadrilátero Ferrífero region, on the Southern tip of São Francisco Craton, is described as a Western-verging, thin-skinned foreland fold-thrust belt that was formed in the Rhyacian, shortly after 2,125 Ma (Alkmim & Marshak 1998).

During the Statherian period, the central sector of São Francisco Craton was rifted and experienced a widespread and intermittent magmatism. The extensional event is represented by the Espinhaço Basin deposition. The Lower Sequence of Espinhaço Supergroup consists of acid to intermediate volcanic rocks and fluvial sediments. The Middle Sequence is composed of quartzite with large-scale crossbedding, and the Upper Sequence consists of a layered sequence of quartzite and pelitic beds deposited in a shallow marine setting (Uhlein *et al*. 1998).

The Rio dos Remédios volcanism was developed in an extensional setting at central Bahia, following the initial deposition of clastic sediments from The Espinhaço Supergroup (Barbosa & Sabaté 2004). It includes several lithostratigraphic units made of conglomerate, sandstone, pelite, carbonate, and diamictite, deposited into continental, transitional and marine systems. The continental systems were described as alluvial fan, fluvial and desertic (Pedreira da Silva 1994).

The Paramirim Aulacogen was formed during successive rifting events between 1,750 and 670 Ma (Pedrosa-Soares & Alkmim 2011). The aulacogen substrate is composed of Archean granites, which were gneissfied and migmatized, in addition to Paleoproterozoic metavolcanosedimentary sequences and granitoids of Siderian, Rhyacian, and Orosirian ages (Santos-Pinto *et al*. 1998, Leal *et al*. 1998, 2000). In the Ediacaran, the aulacogen underwent tectonic inversion (Danderfer Filho 2000, Cruz & Alkmim 2006, Guimarães *et al*. 2012) that extended to the Cambrian. The units that fill the aulacogen belong to the Espinhaço and São Francisco supergroups (Arcanjo *et al*. 2005). The former is represented by a sequence of siliciclastic metasedimentary rocks associated with felsic metavolcanic rocks, whose age of deposition varies between 1,750 and 900 Ma (Chemale Jr. *et al*. 2012). São Francisco Supergroup comprises a sequence of terrigenous and carbonate rocks deposited in a marine environment with glaciogenic influence. In the Northern Espinhaço Range, the Espinhaço Supergroup is represented by the Santo Onofre Group (Schobbenhaus 1996), and in Chapada Diamantina, by the Una Group, subdivided into Bebedouro and Salitre formations (Inda & Barbosa 1978). The Santo Onofre Group has a maximum age of 900 Ma (Babinski *et al*. 2011) and is composed of feldspathic metarenite, meta-quartz sandstone, oligomictic metaconglomerate, phyllite, and metapelite rich in graphite, manganese and sericite (Guimarães *et al*. 2012).

The Neoproterozoic sedimentary cover of the São Francisco Craton was deposited during extensive carbonate-pelitic marine sedimentation after a long-lasting glacial event, whose age is still a matter of debate (Misi *et al*. 2005, 2011). Sedimentary sequences were deposited in two geotectonic environments:

- pelitic-carbonate sediments deposited on the cratonic area, with relatively little or no deformation (Bambuí, Una and equivalent groups);
- siliciclastic and carbonate sediment deposited on the cratonic edges, represented in Bahia by Vaza Barris Group. Glacial diamictites occur at the bases of these sequences (Misi *et al*. 2007).

The Phanerozoic cover evolved during the great extensional event associated with the Gondwana supercontinent fragmentation, whose peak occurred in the Early Cretaceous (Milani & Thomaz Filho 2000).

Borborema Province

The term Borborema Province was introduced by Almeida (1977) and referred to a polymetamorphic and multi-deformed association of tectonic units that were subjected to a significant orogenic event during the Neoproterozoic. The province is composed of a complex network of Neoarchean nuclei surrounded by Paleoproterozoic granitic gneisses, Meso-to Neoproterozoic supracrustal belts, and syn-to late-tectonic Neoproterozoic and Cambrian granites associated with large transcurrent shear zones (Brito Neves *et al*. 2000).

It encompasses nearly the entire Northeastern region of Brazil, covering the states of Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas and Sergipe, besides the Northern part of Bahia (Fig. 1). The province is subdivided into tectonic blocks by branched anastomosing EW- and NE-trending shear zones, which form a mechanically coherent system over more than 200,000 km^2 (Brito Neves *et al*. 2000). The EW-trending Patos shear zone, in Paraíba and southern Ceará, divides the basement of the study area into two domains: Northern and Transversal Zone (Ferreira *et al*. 1998).

The Transversal Zone Domain evolution involved two successive accretionary events, known respectively as Cariris Velhos (*ca*. 1.0 Ga) and Brasiliano (*ca*. 0.6 Ga) (Brito Neves *et al*. 2000). This zone is mainly composed of the Brasiliano Cachoeirinha Belt together with a sequence of pre-Brasiliano terrains, described as Riacho Gravatá, Alto Pajeú, Alto Moxotó, and Rio Capibaribe (Santos *et al*. 2004). The Sm-Nd whole-rock and U-Pb zircon geochronological studies of basement gneisses from Ceará (Fetter *et al*. 2000) allowed the identification of two major pulses of Paleoproterozoic crustal growth within Borborema Province. The first occurred between 2.35 and 2.3 Ga, which is characterized by juvenile growth and accretion, and the second is from 2.19 to 2.05 Ga, involving the amalgamation of new juvenile crustal material, reworked or enriched crust, and Archean crustal fragments. This network of crustal blocks was subsequently affected by an episode of intracratonic rifting at *ca.* 1.8 Ga (Fetter *et al.* 2000).

The Neoproterozoic orogeny that affected the Borborema Province was interpreted as ensialic, because there is no evidence of contemporaneous oceanic crust remnants in the interior domains. An extension-compression stage may be properly applied to the province evolution. This is attributable to a compressive mechanism that later resulted in the extension in an intracontinental setting due to the convergence of São Francisco, Congo, Amazonian, and West African cratons (Neves *et al.* 2000, Neves & Mariano 2004).

A comprehensive step heating $^{40}Ar/^{39}Ar$ investigation, performed on different minerals from igneous and metamorphic rocks, allowed the definition of a consistent, slow cooling history (3–4ºC/Ma) for Borborema Province. It indicated a rather slow uplift rate between 580 and 500 Ma, followed by fast cooling around 500 Ma (Corsini *et al.* 1998). The last magmatic manifestation in Borborema Province occurred from the Cretaceous to the Tertiary. It produced many volcanic and hypabyssal rocks, which occur as dikes, sills, small flows, volcanic conduits and plugs (Sial 1976, Almeida *et al.* 1988).

Based on an investigation of $^{40}Ar/^{39}Ar$ geochronology on tholeiitic diabase dikes, and calc-alkaline basalt, trachyte, rhyolite and ignimbrite, Souza *et al.* (2003) identified four distinct magmatic events in the province, from 145 to 24 Ma. These have been interpreted to reflect the presence of mantle thermal anomalies associated with West Gondwana breakup and, possibly, migration of the South American platform above the Santa Helena plume (Cordani 1970, Chang *et al.* 1992).

Transbrasiliano Shear Zone

The Transbrasiliano Shear Zone (Fig. 1) is regarded as the megasuture that separates Archean and Paleoproterozoic rocks of South America into two major sectors:

- a large Northwestern continental mass, including the Amazonian Craton and Guyana Shield;
- a Southeastern mass, formed by a collage of cratonic fragments that took part in the West Gondwana amalgamation and that includes Borborema Province, São Francisco and Rio de la Plata cratons, as well as other cratonic fragments of southern South America (Schobbenhaus *et al.* 1984).

In both crustal sectors, evolution took place between 3.0 and 1.7 Ga, therefore they were contiguous within a Paleoproterozoic landmass (Cordani & Sato 1999).

A NEW GEODYNAMIC MODEL PROPOSAL

This topic aims to construct a tectonic and temporal framework to characterize the synchronous growth and evolution of Borborema Province and São Francisco Craton. Almost all the cited references discuss the tectonic evolution and crustal structure of the involved terranes, based on isotopic geochronological evidence. The main assumption here is that interpretation of high-quality U-Pb, Pb-Pb and Ar-Ar analyses in carefully chosen samples should be used to constrain the absolute age and duration of common geodynamic processes, such as magmatism, anatexis, deformation, metamorphism, uplift, and post-metamorphic cooling.

Atlantica Paleocontinent

The major cratonic blocks of South America are Guyana Shield, Central Amazonian, Ventuari-Tapajós, Rio Negro-Juruena, Rondônia-San Ignacio, Sunsás, Rio de la Plata and São Francisco. They were accreted between 2.2 and 1.9 Ga ago and formed part of the Atlantica paleocontinent. A hypothesis for the evolution of Atlantica was a fully developed Wilson cycle, associated with a Paleoproterozoic superplume (Teixeira *et al.* 2007). The geological units used by these authors for correlation and reconstruction are:

- obducted remnants of Paleoproterozoic ocean floor basalts;
- large granulite-granitoid Paleoproterozoic orogenic belts;
- thick beds of Archean banded iron formation and associated granite-greenstone belts.

The iron occurrences are present in the Hamersley Province of Western Australia, in the Imataca Block, Venezuela (Cerro Bolivar), São Francisco Craton (Quadrilátero Ferrífero and Guanhães complex), and Borborema Province. Iron formations have been interpreted as representing the remnants of more than 4,000 km long Archean basin, which was transported and overthrust during the Paleoproterozoic orogeny (Teixeira *et al.* 2007), as seen in Fig. 2.

Paleoarchean to Rhyacian: cratonic components

The Gavião Block is composed of granite, granodiorite, and migmatite. It includes remnants of 3.4 Ga-old tonalite-trondhjemite-granodiorite (TTG) suites and associated greenstone belts. The Jequié Block is characterized by Mesoarchean granulitic migmatites with supracrustal inclusions and several charnockitic intrusions (Barbosa & Sabaté 2004). The Serrinha Block is composed of orthogneiss and migmatite, which have been overthrust by Rhyacian greenstone belts (2.2–2.1 Ga), composed of earlier Fe-rich MORB-type tholeiite and later island arc andesite, which are associated with epiclastic and siliciclastic sediments (Silva *et al.* 2001).

Neoarchean to Rhyacian: oceanic stage (2.6–2.15 Ga)

This oceanic stage included widespread basaltic magmatism, which was probably already active 2.6 Ga ago. Two subduction periods have been interpreted. The first occurred within the 2.7–2.5 Ga interval, as deduced from the ages of high-grade metamorphism and partial melting in Curaçá Valley, North of Bahia (Garcia *et al.* 2018, D'el-Rey Silva *et al.* 2007). The second started at about 2.17 Ga and gave rise to restricted calc-alkaline volcanic centers that were associated with massive tonalite plutons. Mafic and felsic volcanic rocks associated with clastic sediments and granitoid intrusions make up the Rhyacian greenstone belts from West Africa (Oberthür *et al.*

1994), Guyana Shield (Voicu *et al.* 2001), and São Francisco Craton (Silva *et al.* 2001).

Rhyacian to Orosirian: continental convergence (2.15–1.9 Ga)

A 4,000 km long granitoid-granulite belt extends from Tandilia in Argentina towards Piedra Alta in Uruguay through Luiz Alves, Mantiqueira, Guanhães and Juiz de Fora regions in Southern and Southeastern Brazil; Jequié, Itabuna, Salvador-Curaçá, Borborema in Northeastern Brazil, Central Guyana; Imataca in Venezuela; and reaches Kenema-Man in Liberia and Ivory Coast (Teixeira *et al.* 2007). This belt is interpreted as part of the large root zone of a mountain chain created during the orogenic event, named Transamazonian in South America and Birimian in West Africa (Fig. 2). The Tapajós-Parima Orogen in Brazil, Venezuela, and Guyana (Santos *et al.* 2001) and the Capricorn Orogen, together with the Gascoyne Province of Western Australia (Cawood & Tyler 2004), were believed to have related to this major high-grade belt (Teixeira *et al.* 2007). The whole collision process could be classified as a gigantic fold-and-thrust belt, in which the main deformation and intrusion of crustal granitoids occurred in the Orosirian, around 2.15 Ga ago.

Orosirian: mantle upwelling (1.9–1.8 Ga)

This stage started after the post-orogenic extensional collapse. A direct consequence was crustal melting together with intrusion of S-type granite plutons, and magma extraction from the upper mantle (Teixeira *et al.* 2001).

Orosirian to Statherian: rifting and continental breakup (1.88–1.76 Ga)

An important mantle activity took place in the Orosirian-Statherian transition and gave rise to widespread continental rifting and magmatism in Amazonian Craton, Borborema Province, and São Francisco Craton. This is attested by the:

- Maloquinha, Iriri, Crepori and Teles Pires volcanism in Northern Brazil (Santos *et al.* 2001);
- Rio dos Remédios volcanism in Bahia;
- Conceição do Mato Dentro felsic volcanic rocks, besides the later mafic dike swarms in Minas Gerais (Silva *et al.* 1995) and Bahia;
- rift-related granites and felsic volcanic rocks in Goiás (Pimentel & Botelho 2001).

The deposition of intracratonic sediments within extensional basins was associated with these volcanic activities.

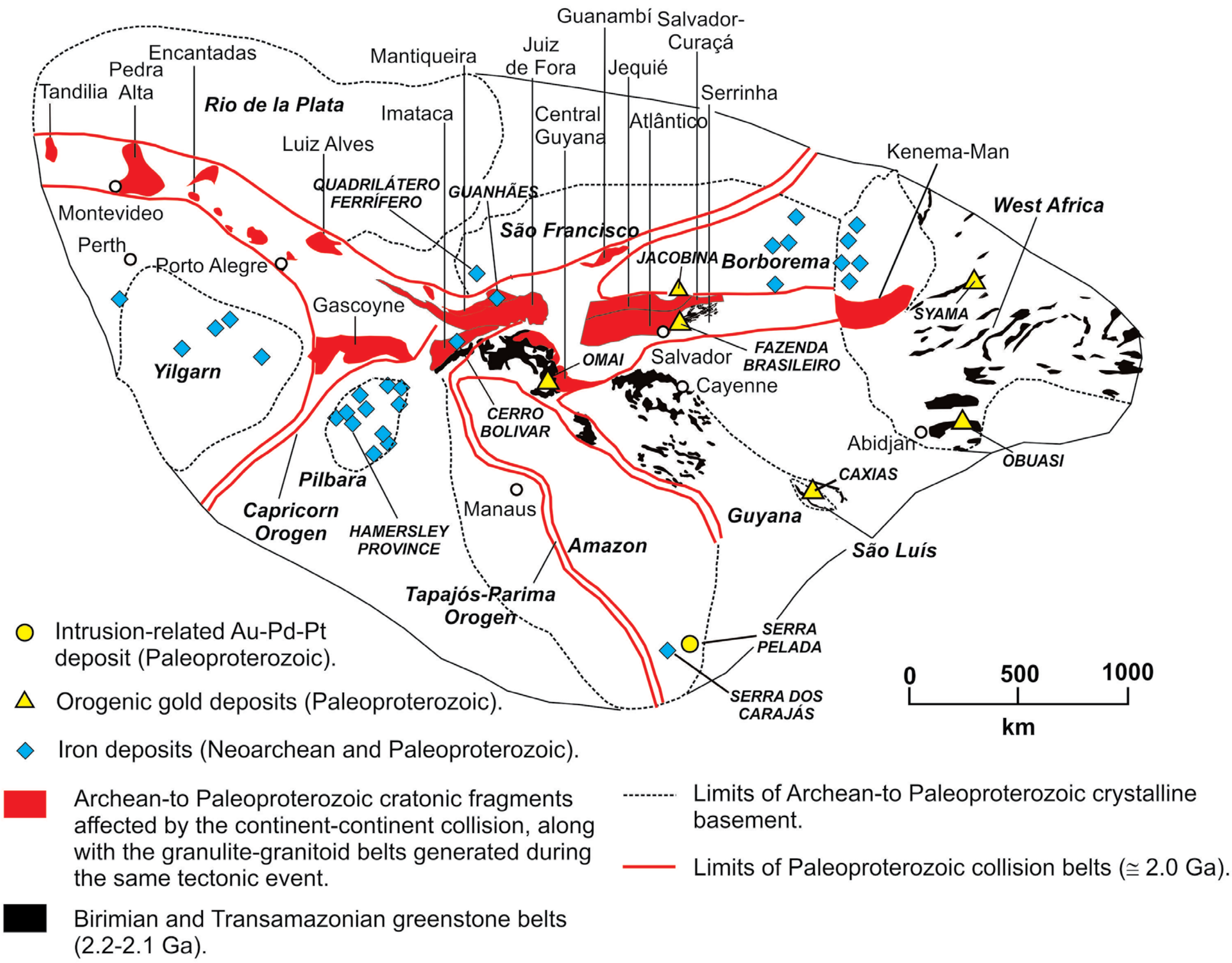


Figure 2. Reconstruction of the Atlantica Paleocontinent at *ca.* 700 Ma ago, modified from Teixeira *et al.* (2007). Source of geological data: Amazonian Craton (Tassinari *et al.* 2000); Guyana Shield (Voicu *et al.* 2001); São Francisco Craton (Barbosa & Sabaté 2004); West Africa (Markwitz *et al.* 2016, Milesi 1989); Borborema Province (Fetter *et al.* 2000); and Western Australia (Portergeo 2019, Cawood & Tyler 2004).

The Gorotire and Beneficente groups in Northern Brazil, the Espinhaço Group in Bahia and Minas Gerais, Mideast Brazil, and the Araí Group in Central Brazil are products of these processes (Dardenne & Schobbenhaus 2000, Pimentel & Botelho 2001). In the 1.88–1.76 Ga interval, a superplume event took place after collision tectonics following the episode of orogenic collapse and mantle upwelling. This event caused rifting, continental volcanism, and emplacement of A-type granites. The result of this episode was the Atlantica breakup, which was fragmented into three main portions: Western Australia, Rio de la Plata-São Francisco, and Amazon-(Guyana)-West Africa blocks (Teixeira *et al.* 2007).

Meso-to Neoproterozoic

Tectonic episodes related to the Grenville orogeny characterize the Mesoproterozoic interval (1,600–1,000 Ma). Until the writing of this paper, in South America, they were recorded only in the Amazonian Craton (Tassinari *et al.* 2000, Cordani *et al.* 2003) forming the Rondônia-San Ignacio belt (1,550–1,300 Ma) and magmatism related to Sunsás orogenic event (1,300–1,000 Ma). It is probable that the 1,000 Ma-old tholeiitic dike swarms in Bahia coastline (Correa-Gomes & Oliveira 2000) were associated with the last stage of Rodinia assembly (Teixeira *et al.* 2007). The breakup of Rodinia (950–600 Ma, Condie 2002a) gave place to the development of Neoproterozoic basins, which are well represented in South America. During the same interval, the first components of the Gondwana supercontinent started to collide (Condie 2002b). It resulted in the development of Goiás Magmatic Arc in Central Brazil, which was formed by accretion of island-arc systems onto the western margin of São Francisco Craton (660–600 Ma, Pimentel & Fuck 1992). The last magmatic events from 670 to 590 Ma are represented by large granite plutons and small layered mafic-ultramafic complexes (Teixeira *et al.* 2007). The most important records of Rodinia breakup are found in the widespread epicontinental and passive-margin basins of the Neoproterozoic (Misi *et al.* 2007). Stratigraphic successions in these basins are represented by glaciogenic, carbonate, and molasse mega-sequences separated by first-order unconformities (Misi 2001, Misi *et al.* 2007).

Absolute age constraints are scarce, due to the absence of volcanic horizons within most of these basins. U-Pb SHRIMP analyses of authigenic zircons, from the volcano-plutonic magmatic event within the Dom Feliciano belt (South of Brazil and Uruguay), provided precise ages of 594 ± 5 Ma (Remus *et al.* 2000). On the other hand, ages on detrital zircons from diamictites at the base of Araçuaí fold-belt, SW of São Francisco Craton, provided a maximum age of 950 Ma for these units. A depositional age of 740 ± 22 Ma was obtained from an 11-point isochron for well-preserved samples of post-glacial successions from Sete Lagoas Formation (Bambuí Group, Minas Gerais, Brazil) (Babinski *et al.* 2007). Due to the scarcity of other reliable absolute ages, correlations between different successions of Neoproterozoic basins were made by means of high-resolution chemostratigraphic studies (Misi *et al.* 2007).

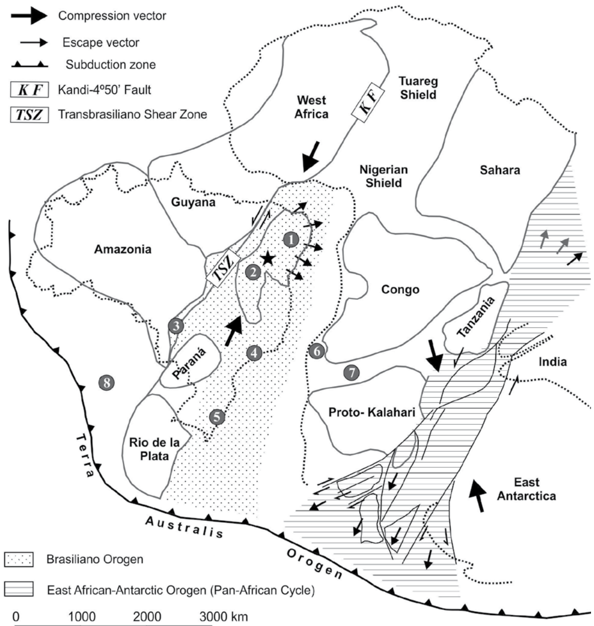
Neoproterozoic to Paleozoic

The Neoproterozoic Adamastor-Brazilide ocean was created during the breakup of Rodinia, which began *ca.* 900 Ma ago. The paleo-ocean started to close at *ca.* 700 Ma ago, as deduced by isotopic data interpretation of magmatic arc granites that occur along the Brazilian shoreline. The final assembling of continental blocks was associated with post-collisional granitoid intrusions during a strike-slip deformation phase between 535 and 500 Ma (Wiedemann 1993, Campos-Neto & Figueiredo 1995, Sanchez-Bettucci *et al.* 2003, Pedrosa-Soares *et al.* 2008, Heilbron *et al.* 2008, Van Schmus *et al.* 2008). The sequence of geodynamic and tectonothermal events related to the opening and closure of Adamastor-Brazilide ocean is broadly referred to as the Brasiliano Cycle (700–450 Ma) in South America, and the Pan-African Cycle in the adjoining Gondwana terranes (Fig. 3).

Brasiliano Orogeny

In a detailed review of the Brasiliano orogenic evolution along the coastline of Brasil (Fig. 3), Alkmim *et al.* (2001) have proposed a sequence of six major stages, based on the nature and approximate duration of each proposed stage:

- the early collision at *ca.* 750 Ma ago, involving the Southern São Francisco and Rio de Plata-Paraná cratons;
- the advanced collision during the 640–620 Ma interval, including the cratonic blocks of Amazonia, São Luís-West Africa, Parnaíba, São Francisco-Borborema, Central Goiás-Tocantins, Congo-Angola, Rio de la Plata, Kalahari,



Source: modified from Teixeira *et al.* (2010).

Figure 3. The major orogenic belts of West Gondwana *ca.* 650 Ma ago. Source of geological data: Brasiliano Orogeny (Heilbron *et al.* 2008, Alkmim *et al.* 2001, Alvarenga *et al.* 2000, Brito Neves *et al.* 2000); East African-Antarctic Orogeny (Jacobs & Thomas 2004); Terra Australis Orogeny (Cawood 2005). The numbered circles refer to the following lithotectonic units: (1) Borborema Province; (2) São Francisco Craton; (3) Paraguay Belt; (4) Ribeira Belt; (5) Dom Feliciano Belt; (6) Kaoko Belt; (7) Damara Belt; (8) Pampean Belt. The black star marks the position of Irecê Basin.

Pampia, and Arequipa (Schobbenhaus & Brito Neves 2003), whose convergence generated the east-verging nappes in the Southern arm of Brasília fold belt;
- the collision completion of the Amazonian Craton with the Parnaíba block, which gave rise to the Northern arm of the Brasília fold belt.

Important contributions were made by other groups:
- creation of Ribeira dextral-transpressional zone between 790 and 610 Ma, and incorporation of exotic terranes of Southeastern Brazil during the Cambrian between 535 and 500 Ma (Heilbron *et al*. 2008);
- convergence between Rio de la Plata-Paraná and Amazonian cratons, which gave rise to the Paraguay orogenic belt between 540 and 510 Ma (Alvarenga *et al*. 2000);
- Northward progression of the Brazilide ocean closure, which produced the dextral extrusion of Borborema Province in the Cambrian between 540 and 500 Ma (Brito Neves *et al*. 2000), along with thrusting over the Northern margin of São Francisco Craton. Southward propagation of thrusting caused rock deformation of Paramirim valley and Chapada Diamantina (Alkmim *et al*. 2001).

East African-Antarctic Orogeny

The East African-Antarctic orogen resulted from a collision of various blocks of proto-East and West Gondwana between 650 and 500 Ma (Fig. 3). This ~8,000 km long, Northeast-southwest-trending collisional belt encompassed several microplates that were amalgamated and dislocated along strike-slip faults (Jacobs *et al*. 1998). At some stage, during the orogeny, these faults provided a means of tectonic transport from the collision zone toward the subduction zone of Terra Australis orogen (Cawood 2005), which is located to the South (Fig. 3). This event was the generator of lateral-escape tectonics in the Southern part of East African-Antarctic orogen (Jacobs & Thomas 2004).

According to Doblas *et al*. (2002), a Cambrian tectonothermal event immediately followed the peak of Pan-African-Brasiliano compression. Overriding thermal insulation was caused by the thick lithosphere of West African Craton, leading to progressive temperature increase in the sub-continental lithospheric mantle. The subcratonic heat accumulation phenomenon was followed by thermal activity, which was the main cause for the circum-West African Craton delamination and sinking of the thickened roots of Pan-African-Brasiliano mountain chain. This important tectonothermal event was propagated along the border of proto-West Gondwana (Fig. 3) between 530 and 510 Ma (Heilbron *et al*. 2008). The best examples are described in Búzios orogeny of Ribeira Belt (Schmitt *et al*. 2004), in the Kaoko and Damara belts (Goscombe & Gray 2007), and also in Paraguay-Araguaia (Alvarenga *et al*. 2000), Dom Feliciano (Bossi & Gaucher 2004), and Pampean orogenic belts (Rapela 2000).

Cambrian wrench-faults in Eastern Brazil

A large-scale wrench-fault system produced the dominant style of breakdown and dislocations in the Borborema-São Francisco block during the Cambrian (Fig. 3). The reasoning is as follows:
- Evolution of East African-Antarctic Orogeny was almost parallel to, and coeval with that of the Brasiliano orogeny (Fig. 3) between 570 and 520 Ma (Cawood & Buchan 2007). An escape tectonics system has been correctly proposed for the Southern tip of East African-Antarctic orogen (Jacobs & Thomas 2004). The same regime is likely to have occurred in Borborema-São Francisco terrane, in order to accommodate the dislocated crustal fragments (Fig. 3);
- The Transbrasiliano Shear Zone (Fig. 3) was interpreted as the Kandi-4º50 lineament prolongation in the Hoggar, a Pan-African suture at the margin of West Congo Craton (Caby 2003, Arthaud *et al*. 2008);
- Although an outstanding set of transcurrent, ductile shear zones have been described in Borborema Province (*e.g*. Santos & Brito Neves 1984, Jardim de Sá *et al*. 1992, Vauchez *et al*. 1995, Arthaud *et al*. 2008), only a few large-offset strike-slip faults have been recognized in São Francisco Craton (*e.g*., Schobbenhaus *et al*. 2004 — see Fig. 1) until the writing of this text.

A new deformation pattern is proposed here, with paleostress field and observable and hidden ruptures affecting the post-Brasiliano Borborema-São Francisco terrane shown in Figure 4.

Based on their geometry and regional distribution, these regional structures are here interpreted as right-lateral and left-lateral strike-slip faults. They are related to the incidence of escape tectonics and formation of *en echelon* compressional structures in the Northern sector of Brasiliano Orogen. This can be described as a process of wrench-fault tectonics that produced the last stage of crustal deformation, uplift, and erosion in the Cambrian Period. The majority of these concealed fault zones have been recognized in the interpretation of Bouguer gravity anomaly map from Bahia State (Gomes *et al*. 1996).

TECTONIC FRAMEWORK OF BAHIA

The published geological maps of Bahia State do not refer to post-Neoproterozoic tectonic or plume activities. The following section describes for the first time the effects of a massive thermotectonic process that took place in the 540–500 Ma interval in Bahia State, and which caused a large brittle-ductile deformation of Archean and Proterozoic terranes, accompanied by pervasive heat flux, hydrothermal activity, and crustal melting. This deformation is classified as a wrench-fault system, composed of strike-slip faults that caused terrane displacements in excess of 300 km (Fig. 5).

The observed effects of this thermotectonic process in the Northern and Mid-eastern sectors of Bahia are listed as follows:
- In the Irecê Basin, North of Chapada Diamantina, a set of thin-skinned folds affected the carbonatic sequences of the Salitre Formation. These structures exhibit surface features oriented around the E-W direction, with general vergence towards the South (Kuchenbecker *et al*. 2011);

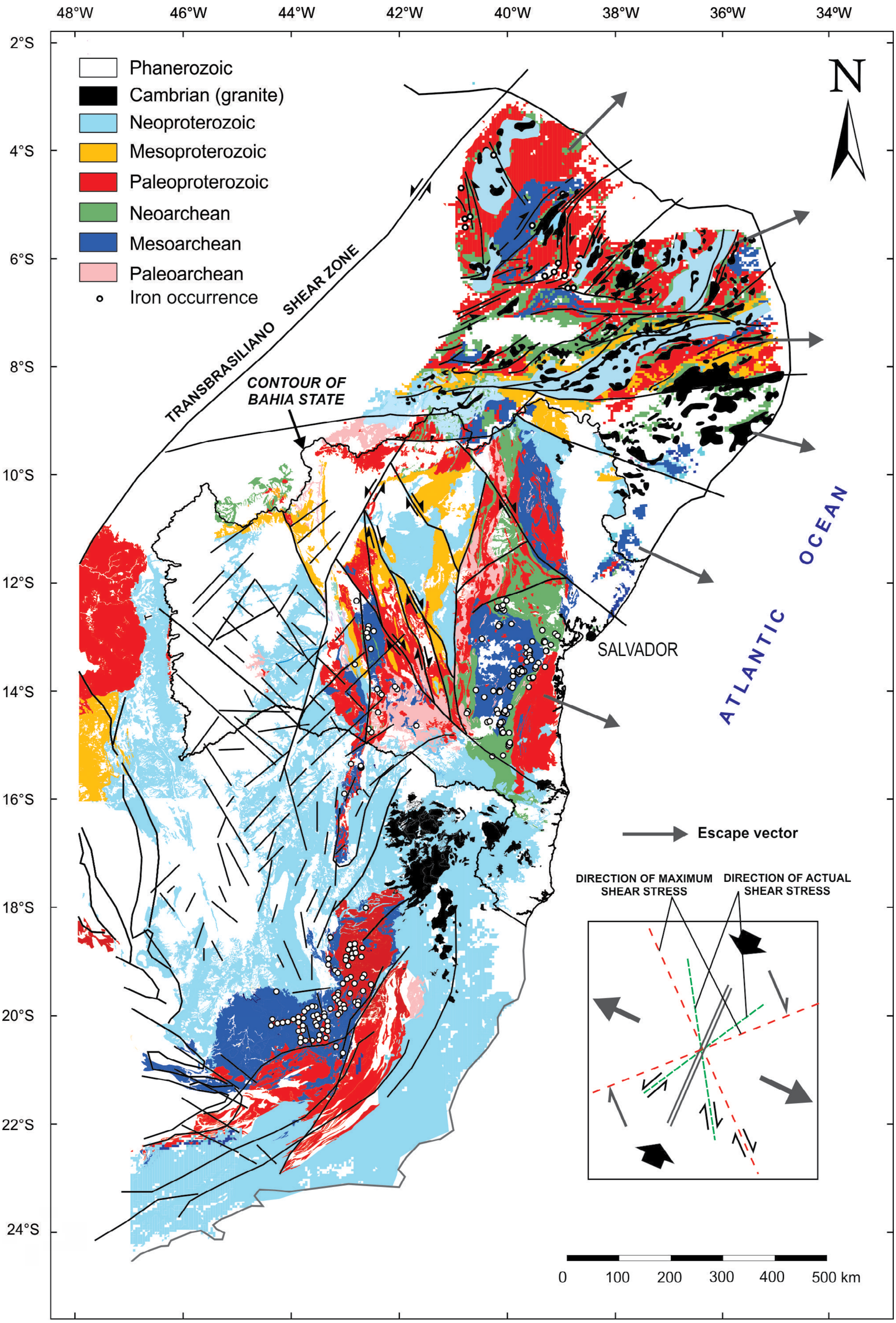


Figure 4. Wrench-fault model applied to the Cambrian deformation of São Francisco Craton along Borborema Province. Some of the Northwest-southeast trending fault zones in São Francisco Craton form an *en echelon* pattern and indicate large dextral dislocations, which overall appear to be as great as 300 km. The main reference parameters for estimating displacement are the relative dislocations of Archean and Proterozoic units along the rows of previously aligned Archean iron occurrences. The diagram for the shear stress directions is an approximation for a theoretical stress ellipsoid in homogeneous media. Most faults must have resulted from horizontal stresses, due to lateral compression. Geological units are after Schobbenhaus *et al.* (2004).

- Samples of Cryogenian carbonates of Irecê Basin have similar Pb-Pb isochron ages and paleomagnetic poles. These fall close to the ~520 Ma segment of Gondwana supercontinent apparent polar wander path, after rotation of South America to Africa. This indicates that the resetting of the isotopic and magnetic systems occurred at that Cambrian moment (Trindade *et al.* 2004). Data from alternating field demagnetization and thermal treatments indicated monoclinic pyrrhotite, magnetite, and hematite as the carriers of more stable magnetic components in the carbonatic rocks. This Cambrian remagnetization was attributed to a regional-scale fluid migration event and mineralization in the aftermath of Brasiliano collision (Trindade *et al.* 2004);
- In the Northern sector of Curaçá Valley, more precisely in the region of Curaçá town. The carbonate sequence of Estância Domain (Neoproterozoic of the Sergipano Fold Belt) is clearly pushed to the South and thrust onto the basement (Oliveira 2012);

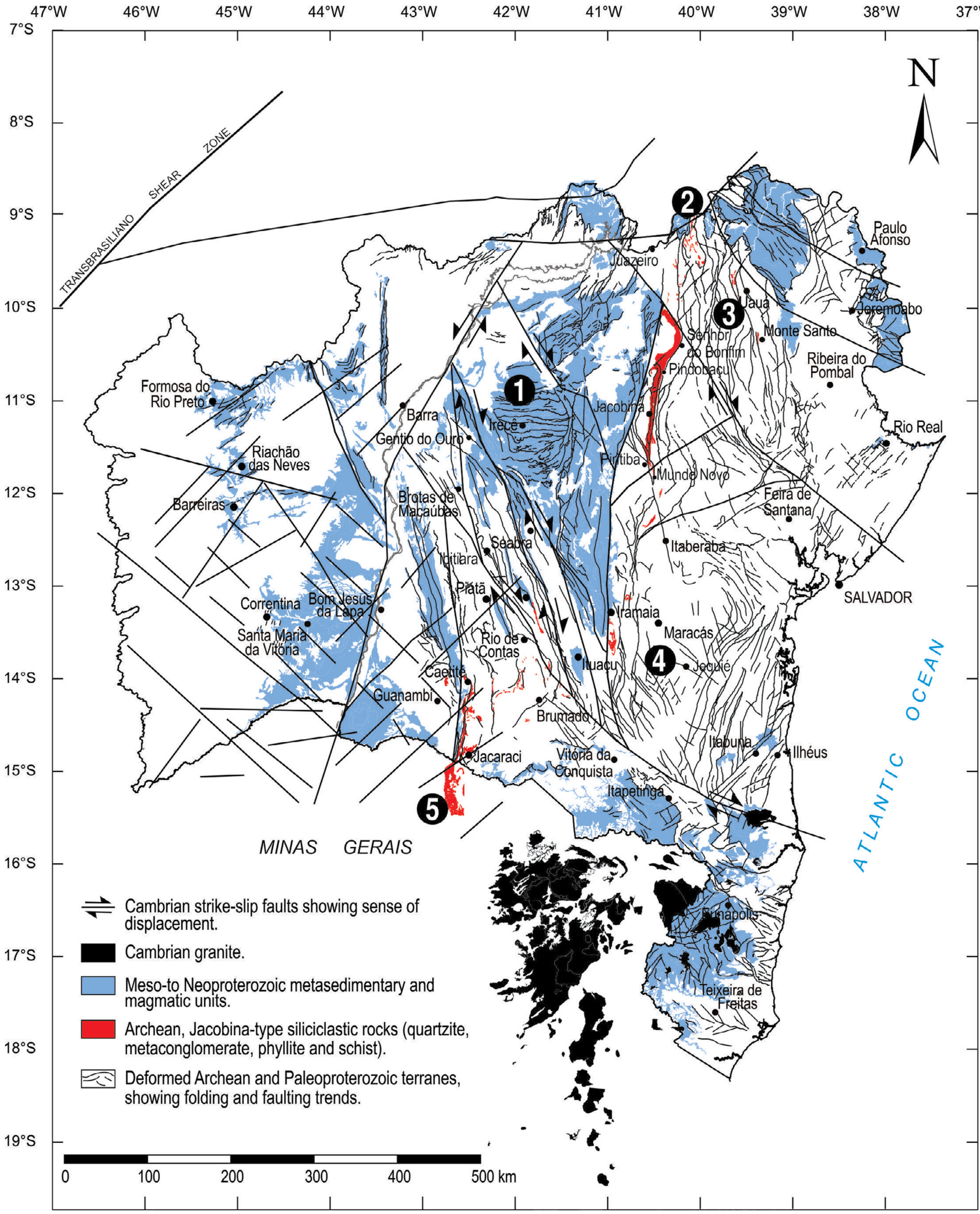


Figure 5. Tectonic framework of Bahia State as proposed in the present study. Circled numbers stand for key locations referred to in the text: (1) Irecê Basin; (2) Curaçá Valley; (3) Jacurici Cr-District; (4) Rio Jacaré layered sill, and (5) siliciclastic, Jacobina-type metasedimentary rocks. Source of Archean and Proterozoic units along with their structural trends: modified from Misi *et al.* (2012).

- In the Jacurici Chromite District, where a brittle regime responsible for the formation of oblique fractures and faults with dextral and sinistral directional components closes the cycle of structural evolution of the area;
- In the layered Rio Jacaré sill, which was intruded at around 2,700 Ma at the West edge of Jequié Block, where NNW-oriented strike-slip faults cut all pre-existing structures (Brito 2000);
- Finally, the regional distribution of Archean siliciclastic, Serra de Jacobina-type (quartzite, conglomerate, phyllite and schist) metasedimentary rocks. These extend from North to South in the territory of Bahia and continue Southward in the State of Minas Gerais, but strongly displaced from their initial position by the effect of Cambrian wrench-fault system (Fig. 5).

RECONSTRUCTION HYPOTHESIS

An attempt to reconstruct the São Francisco-Borborema block after the Rhyacian continental collision is discussed here. The most significant issues to be taken into consideration in this large-scale reconstruction are:

- counter-clockwise rotation of Borborema Province due to relative displacements along transcurrent shear zones;
- displacement of Archean and Proterozoic terranes of central Bahia in the Northwest direction, along *en echelon* compressional faults in the Northern sector of Brasiliano Orogen.

The interpreted displacements can reach distances up to 300 km. This is called the "minimum fault offset model", because it does not include any paleomagnetically based displacement data. In conformity with the present hypothesis, the chronostratigraphic units of São Francisco Craton are characterized by several dextral and sinistral strike-slip fault zones. Much of this displacement took place during the Cambrian and provoked generalized breakdown and uplift of Archean and Proterozoic massifs within the Paleoproterozoic orogenic belt.

The reconstruction procedure of São Francisco-Borborema block consisted of the restoration of some NW-SE trending strike-slip fault zones, which indicate horizontal dislocations of *ca.*100 to 300 km. This is deduced from the large-scale tectonic breaks and displacements of individual components of Archean basement, Proterozoic basins, and formerly aligned iron occurrences.

The Borborema shear zone system is one of the largest lithospheric transcurrent shear zone systems in the world. Nevertheless, the amount of displacement accommodated by shear zones remains uncertain, because suitable markers are missing, which preclude any direct estimate (Vauchez *et al.* 1995). Regardless of the amount and sense of displacement along discrete shear zones, the present reconstruction simply outlines the counterclockwise rotation of Borborema Province in relation to the São Francisco Craton. This leads to the alignment of three different Archean sequences and Proterozoic basins, as well as overthrust Archean iron deposits (Fig. 6).

Hydrothermal gold deposits in Bahia

Primary gold mineralization in Bahia State is associated with deformed and metamorphosed rocks of Mesoarchean, Neoarchean, Paleoproterozoic, and Neoproterozoic ages. Gold essentially occurs in quartz veins and hydrothermal altered zones, generated during two main tectonothermal events, i.e. Paleoproterozoic and Cambrian, respectively.

Considering the current production data, allied to knowledge of geology and metallogenesis of operating mines, deposits, occurrences and prospects or *garimpos* (artisanal diggings), three hydrothermal gold provinces are discerned:

- Middle Rio Itapicuru;
- Serra de Jacobina;
- Western Chapada Diamantina.

In all these provinces, gold occurs in hydrothermal veins, which are usually associated with quartz and iron sulfide minerals.

Locations of three main auriferous provinces of Bahia together with other deposits and gold occurrences are shown in Figure 7.

Middle Rio Itapicuru Gold Province

The Rio Itapicuru greenstone belt is a metavolcanosedimentary association of Paleoproterozoic age, which is formed by mafic metavolcanic rocks at the base, felsic metavolcanic rocks in the intermediate part, and metasedimentary rocks in the upper part. About 180 km in the approximately N-S direction, this province contains two mines in operation: Fazenda Brasileiro (Teixeira *et al.* 1990) and C1 (Teixeira & Coelho 2014, Assis & Luvizotto 2018), one gold deposit (Deixaí), and a few dozen occurrences and small prospects, located mainly at North of Itapicuru River (Fig. 8).

Gold mineralization in Rio Itapicuru greenstone belt was generated in an orogenic environment, resulting from the collision of a volcanic island arc system, associated with ocean-floor basalts of Paleoproterozoic age, with an Archean continental margin. This collision resulted in metamorphic-deformational processes under a compression-to-transpressional regime, which produced a significant increase in temperature and pressure gradients on a regional scale (Silva *et al.* 2001). The first $^{40}Ar/^{39}Ar$ dating of sericite in hydrothermal haloes around gold-bearing quartz veins of Fazenda Brasileiro produced minimum cooling ages, around 2,031 and 2,083 Ma (Vasconcelos & Becker 1992). These figures were refined by Mello (2000), who produced ages of 2,050 ± 4 Ma and 2,054 ± 2 Ma for the same type of sericite cooling. These ages are roughly coeval with crystallization of the surrounding syntectonic granitoids (Alves da Silva *et al.* 1993) and indicate that Fazenda Brasileiro mineralization was contemporaneous with the Rhyacian collision (syn collisional mineralization).

Serra de Jacobina Gold Province

Gold deposits in the Serra de Jacobina region in Bahia occur in a belt of siliciclastic metasedimentary rocks intercalated with mafic and ultramafic rocks and underlain by a TTG basement (Fig. 9).

The siliciclastic sequence probably represents remnants of an Archean sedimentary basin (Teles *et al.* 2015), which was subsequently subjected to a complex history of deformation, metamorphism, granite intrusion, and hydrothermal activity, as a result of oblique collisional events in the Neoarchean and Paleoproterozoic (Teixeira *et al*. 2001), as seen in Figure 10.

Gold in Jacobina occurs in quartz veins and veinlets. They fill tension gashes and open fractures related to semi-concordant shear zones hosted by quartzites and andalusite-graphite-quartz schist, and also local metaconglomerates of Rio do Ouro Fm. Regardless of the host rock composition, mineralized bodies present hydrothermal alteration associations containing pyrite, pyrrhotite, quartz, sericite, fuchsite, and tourmaline (Teixeira *et al*. 2001).

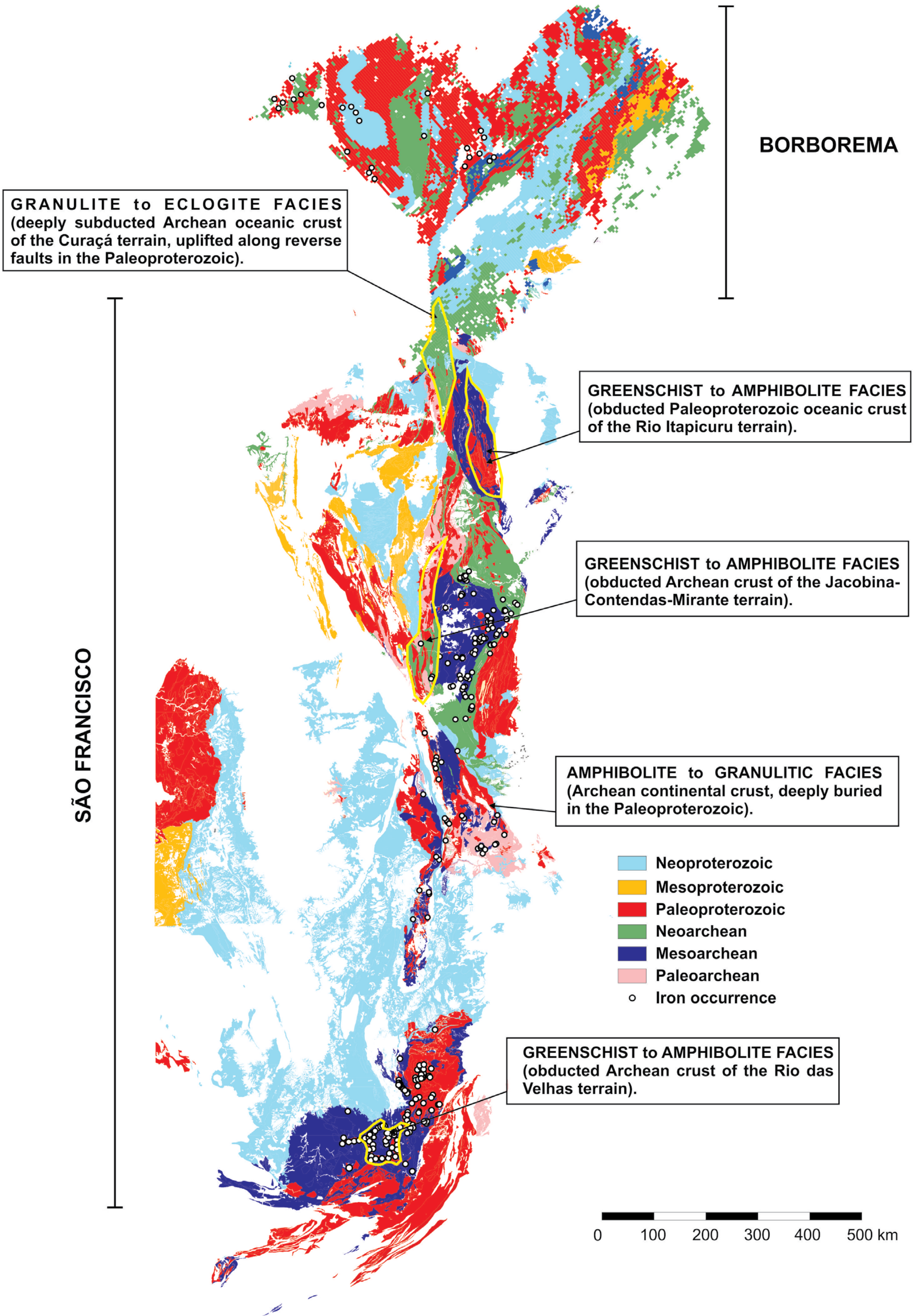


Figure 6. Reconstruction of São Francisco-Borborema block in the interval between the Rhyacian continental collision and Cambrian tectonothermal event, involving rotation of Borborema Province and restoration of São Francisco Craton along dextral, strike-slip faults.

The earlier syngenetic hypothesis, in which gold was deposited together with clastic grains in Serra do Córrego basal conglomerate reefs (*e.g.*, Davidson 1957, Bateman 1958, Sims 1977) is questionable, because the mineralized zone thickness is excessive. Gold occurs throughout the lower and upper metaconglomerate intervals, whose total thickness reaches approximately 290 m (Teixeira *et al.* 2001). Alternatively, the Serra do Córrego mineralization may be considered as orogenic, generated in an accretionary environment, during the melting of crustal rocks, shortly after the Rhyacian continental collision. The argon thermochronology carried out by Ledru *et al.* (1997) restricts hydrothermal alteration processes

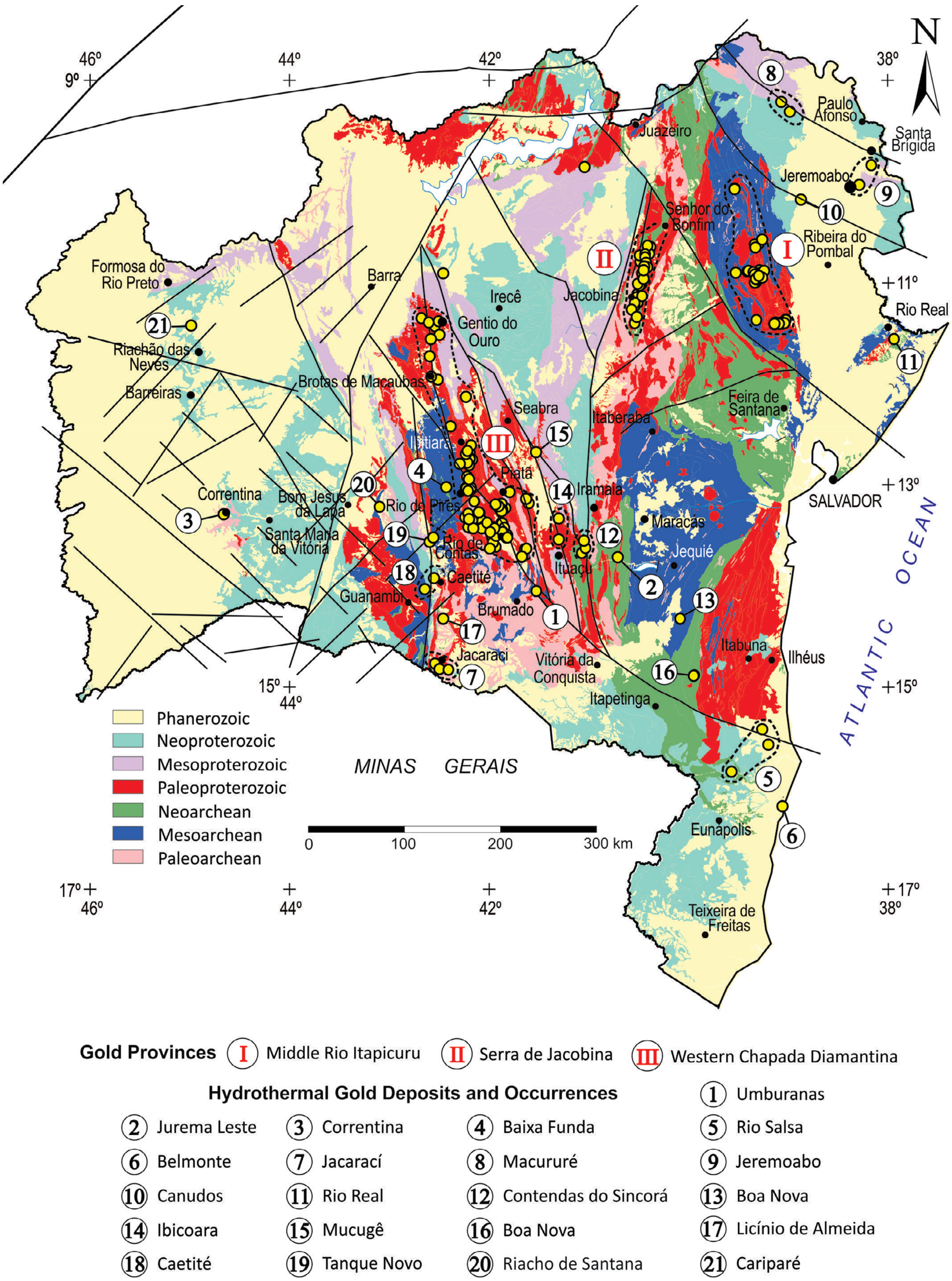


Figure 7. Location of hydrothermal gold mineralizations in Bahia State. Geological units after Schobbenhaus *et al.* (2004). Source for the structural framework: present work. Source for location of gold deposits and occurrences: Misi *et al.* (2012).

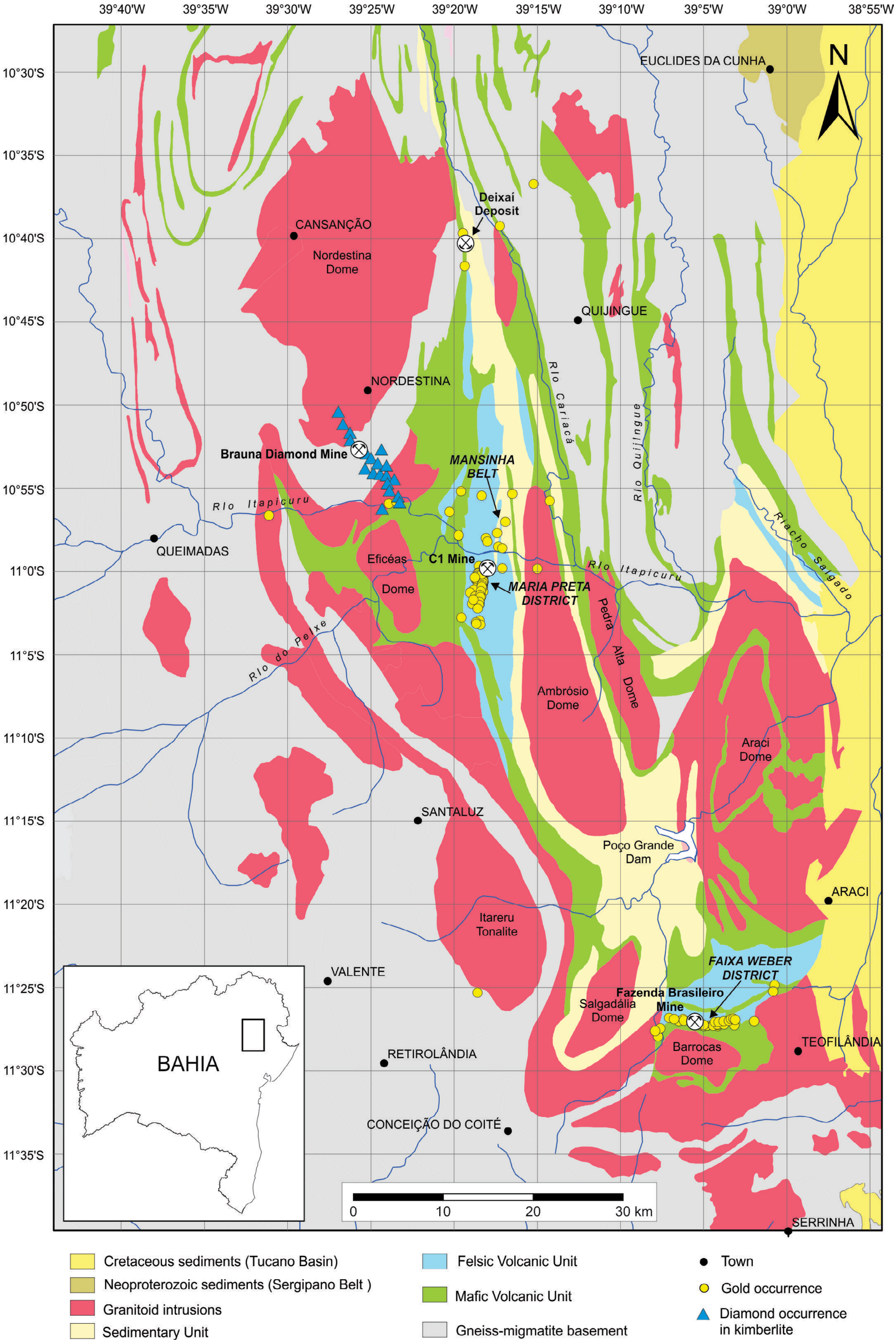


Figure 8. Geological map of Rio Itapicuru greenstone belt showing location of mines, deposits and gold occurrences, along with the location of diamond deposits. Source for geological units and mineral occurrences: Misi *et al.* (2012).

to the period from 1,943 to 1,912 Ma, which is undoubtedly contemporaneous with the emplacement period of peraluminous granites in the region, from 1,970 to 1,800 Ma. Serra de Jacobina gold mineralization is therefore interpreted as an integral part of the late (~1.9 Ga) tectonothermal evolution of the region. It was roughly coeval with the emplacement of large volumes of post-collisional, peraluminous granitic magmas, during a regional strike-slip regime (Teixeira *et al.* 2001).

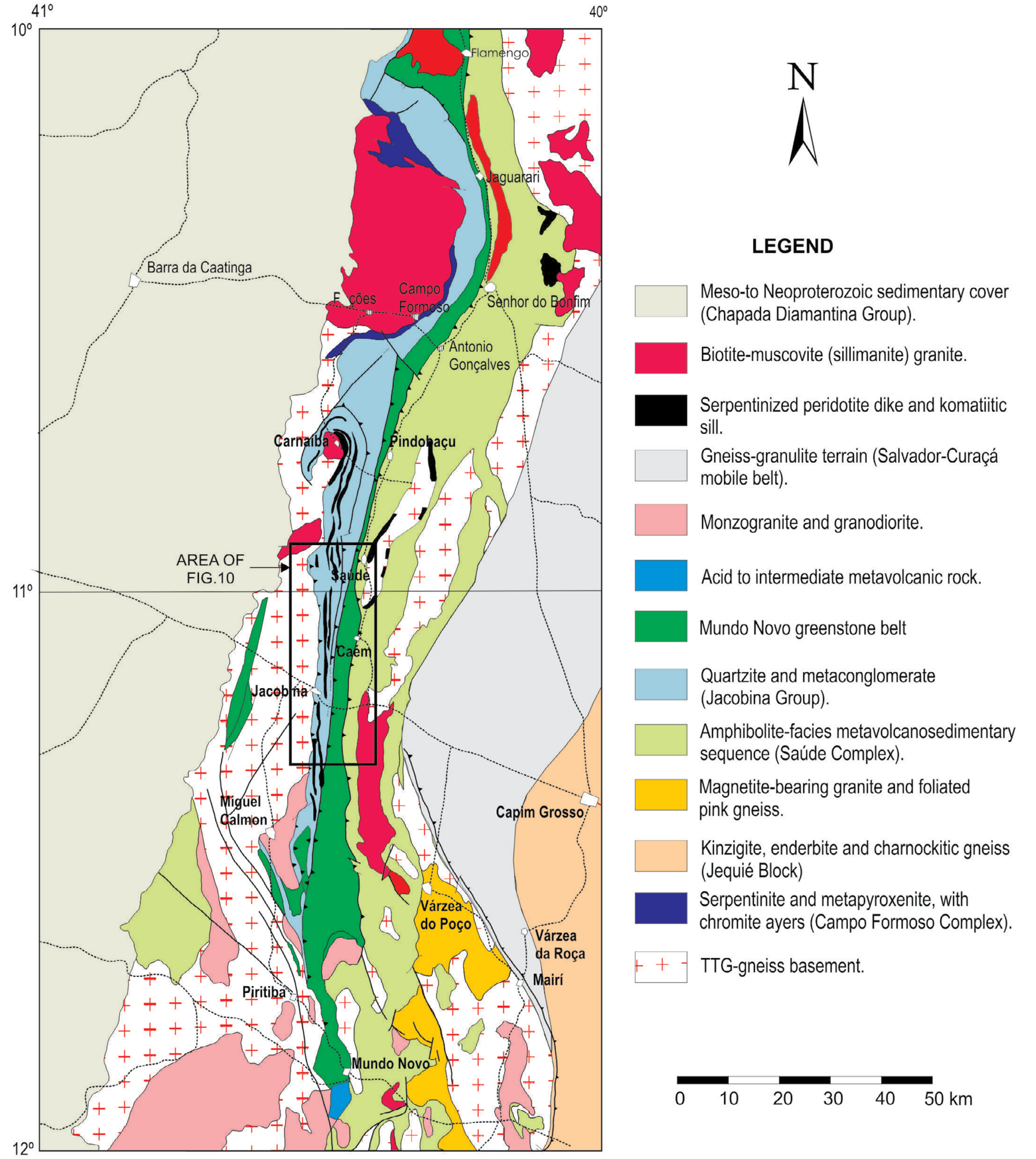
Western Chapada Diamantina Gold Province

Gold deposits in Western Chapada Diamantina are grouped into six different districts, respecting their spatial distribution, with structural sub-divisions in Gentio do Ouro, Ibitiara, Baixa Funda, Catolés, Paramirim, and Rio de Contas. Production in Chapada Diamantina Province comes from *garimpos*, generally with very low mechanization (Fig. 11).

The main gold mineralization in Gentio do Ouro District is associated with quartz veins hosted in hydrothermally altered, schistfied, and/or mylonitized basic sills. The latter are sub-concordant to the stratification of metasedimentary rocks of Espinhaço Supergroup. The main mineralized areas are located on the flanks of Ipupiara Anticline, associated with shear bedding-parallel laminated veins, as well as with oblique or *en echelon* extension veins (Loureiro *et al.* 2008).

Gold and barite mineralization from Ibitiara to Rio de Contas region occurs in:

- boudined veins controlled by NNW-SSE shear zones developed in sedimentary rocks of Espinhaço Supergroup;

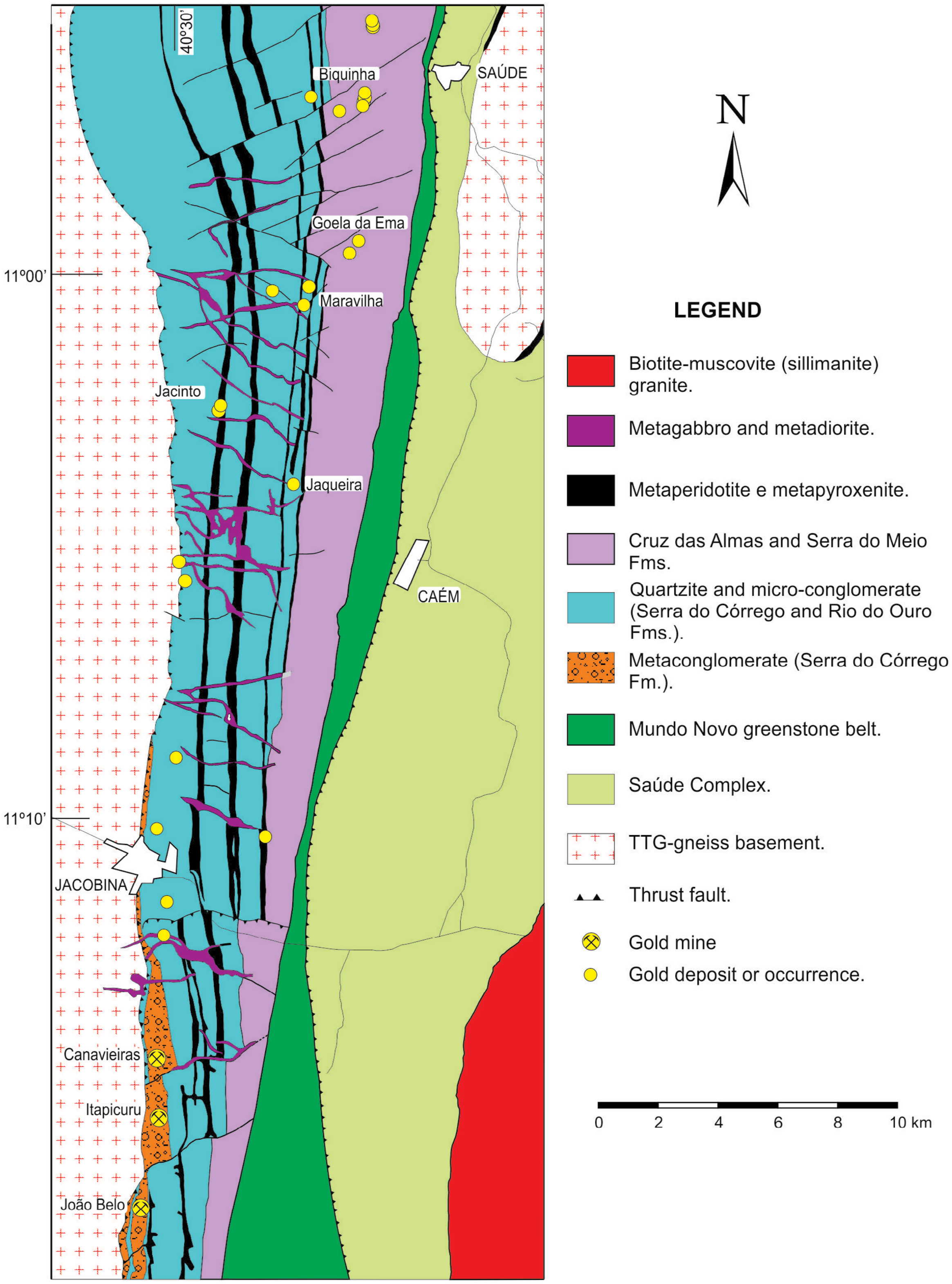


Source: modified after Mascarenhas *et al.* (1998).

Figure 9. Geological map of Serra de Jacobina region. Widespread Phanerozoic sedimentary cover has been omitted for clarity purposes.

- in volcanic, subvolcanic and sedimentary rocks of Rio do Remédios Group;
- in sedimentary rocks of Paraguaçu Group. The immediate host rocks of gold veins are usually mylonitized and hydrothermally altered, with development of sericite, hematite, and carbonate.

Gold grades are erratic and vary from 2 to 3 g Au/t. Hydrothermal breccias usually mark the contact of veins with host rocks (Silva *et al.* 2006, Guimarães *et al.* 2008). The $^{40}Ar/^{39}Ar$ data of sericite from samples collected from shear zones immediately adjacent to the veins revealed Cambrian cooling ages, in the range of 500 to 497 Ma (Silva *et al.* 2006). Gold mineralization in Western Chapada Diamantina was generated in a post-orogenic environment, resulting from the collision of South American and African terranes, during the amalgamation of West Gondwana paleocontinent.



Source: modified after Couto *et al.* (1978) and Mascarenhas *et al.* (1998).

Figure 10. Geological map of the central part of Serra de Jacobina region. Source for gold occurrences: Misi *et al.* (2012).

The Lavra Velha gold and copper deposit, in Ibitiara District, is the first in this province that underwent rational exploration in modern times. The deposit is characterized by an association of hydrothermal breccias hosted in altered granite and acid-to intermediate subvolcanic rocks. These are cut by a system of veins and veinlets, consisting predominantly of an association of hematite, tourmaline, quartz, and sericite. The breccias and veins have irregular branched structures of unknown extension, with a general N30°-50°E orientation. The Lavra Velha mineralization is hosted by sulfide breccias. The gold content ranges from 5 to 50 ppm, while the copper content varies from 0.2% in areas with disseminated chalcopyrite to 8% in zones richer in bornite (Campos 2013).

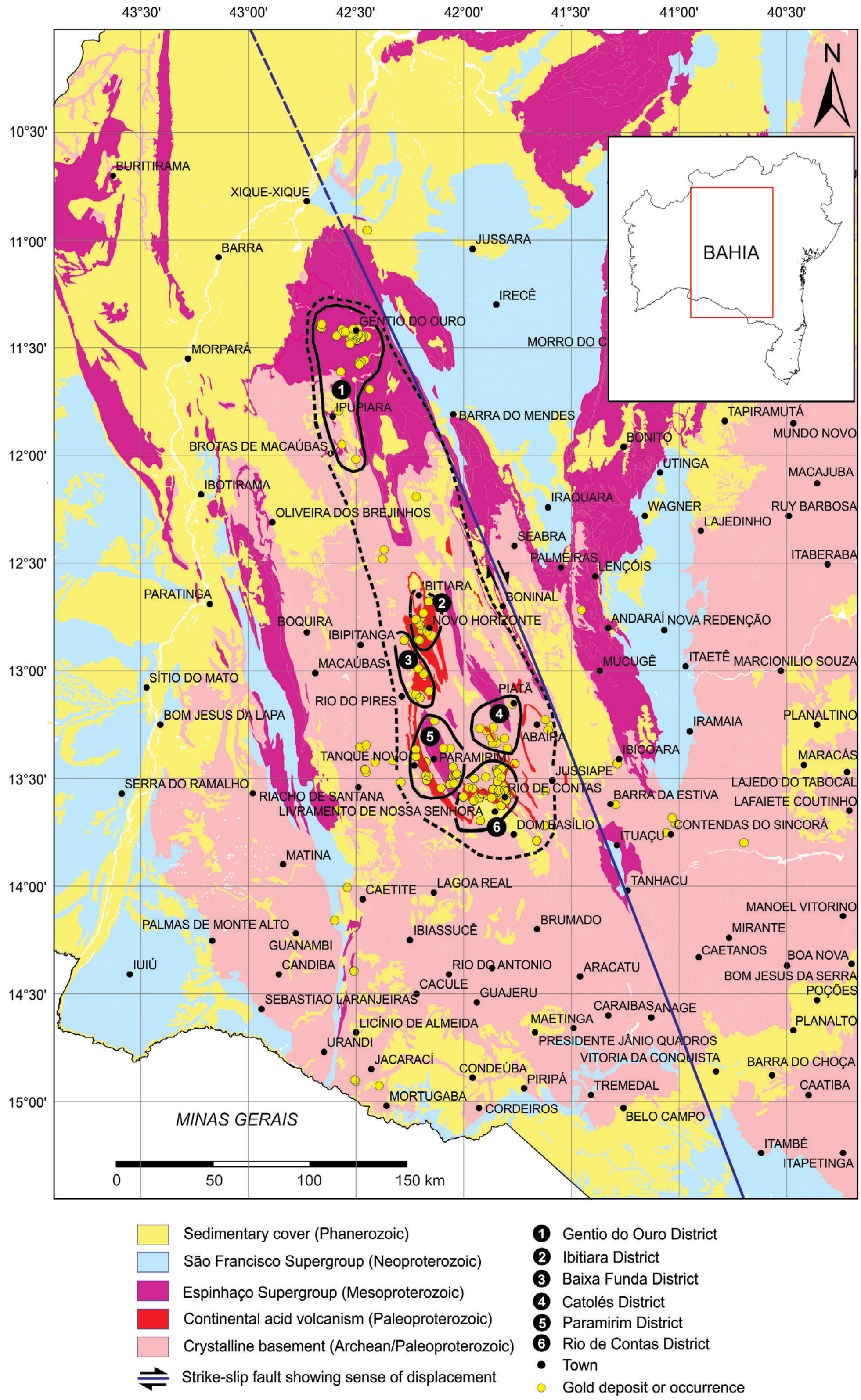


Figure 11. Geological outline showing the location of Western Chapada Diamantina Gold Province. Source for geological units: Schobbenhaus *et al.* (2004). Source for location of gold deposits and occurrences: Misi *et al.* (2012).

Published reports from Yamana Gold, related to their early gold-copper exploration project, suggest that the Lavra Velha project represents a regional mineralization believed to be an IOCG system characterized by sub-horizontal mineralized levels. According to this mining company, mineralization control suggests close affinity to the volcanic-plutonic contact that likely acted as a structural/chemical boundary. The inferred mineral resource was calculated at 3.9 million tonnes at 4.29 g/t containing 543,000 ounces of gold" (Yamana Gold, Mid-Year 2018 Exploration Update). There are no published data regarding copper reserves in Lavra Velha deposit.

DISCUSSION

This paper reviewed the existing concepts regarding the geotectonic evolution of Bahia, in the framework of the Northeastern region of Brazil. Most of these concepts have remained relatively simple for decades (*e.g.* Almeida 1977, Barbosa & Sabaté 2004) and do not accommodate the requirements necessary to explain the crustal evolution and associated metallogenic processes that occurred in the region. A regional metallogenic analysis was undertaken to better understand the origin and geodynamic setting of each gold province in Bahia. The main assumption is that a primary ore deposit stands as the product of specific geodynamic systems, and consequently, ore provinces are real markers of multiple thermotectonic events.

The basement of crystalline rocks of the São Francisco-Borborema block consists of large Archaean continental terranes, formed between 3,500 and 2,500 million years ago, in different regions of the planet. These terranes were accreted during plate convergence about 2 billion years ago, in the context of Atlantica paleocontinent. The continental accretion occurred in a thrust belt system, which caused crustal thickening, and created a 500 km wide mountain chain.

A superplume event occurred after collision tectonics and following the episode of orogenic collapse and mantle uplift. This event caused rifting, generalized volcanism, and placement of anorogenic granites, in the interval between 1,880 and 1,760 Ma. The result was a rupture of the Atlantica paleocontinent. Following the superplume event, a new agglutination of continents took place, witnessed by the presence of rocks from the Grenville Orogeny, which resulted in the Rodinia paleocontinent construction.

The Rodinia paleocontinent fragmentation extended from 900 to 600 Ma. Generalized geological features that mark this in South America as well as in Africa are the epicontinental Neoproterozoic basins. In Brazil, the carbonate-siliciclastic sedimentary rocks of Bambuí Group, distributed in Minas Gerais (São Francisco Basin) and Bahia (Irecê, Una-Utinga and Campinas), represent these basins. Some fragments of Rodinia moved around the planet, amalgamated and formed the Gondwana paleocontinent. The main accretion event, namely Brasiliano/Pan-African, started about 770 Ma and continued until about 480 million years ago, in the Ordovician Period.

During the Neoproterozoic-Cambrian transition, the region corresponding to the Northeastern sector of Brazil experienced extreme brittle-ductile deformation, caused by oblique convergence and collision of the West African Craton (then attached to the Guyana Shield). This resulted in the establishment of large strike-slip fault systems, distributed according to a major, coupled NW-SE and NE-SW directed pair. The overriding heat flux and fluid movement during this process, in the 520 to 515 Ma interval, caused resetting of isotopic and magnetic systems in the carbonate rocks of São Francisco and Irecê basins. The final tectonic event related to amalgamation of West Gondwana in South America was the extensional collapse of the thickened orogenic crust. The expressive pressure relief attributed to this process led to the production of voluminous postcollisional granitic and syenitic bodies.

São Francisco-Borborema block is suggested to have been reconstructed at *ca.* 700 Ma in this paper. The best-explored correlation elements have been the:

- Archean and Proterozoic lithotectonic units and their Paleo-, Meso- and Neo- respective subdivisions;
- Birimian and Transamazonian (> 2,200–2,100 Ma) tholeiitic magmatism, which represents the oceanic phase of a Rhyacian Wilson cycle;
- granulite-granitoid remnants of large orogenic belts, which represent the collision phase of the same Wilson cycle;
- iron provinces, which have been interpreted as belonging to the same Neoarchean basin (Teixeira *et al.* 2007).

The proposed new wrench-fault model is related to the Cambrian to Early Ordovician shortening event of the Eastern part of South America. This tectonic model resulted from empirical observations and serves mostly to:

- reconcile the unlikely discrepancy between the geotectonic evolution and deformation styles currently described for the Borborema Province and the São Francisco Craton;
- present an explanation for the segmentation and relative displacements registered by the discontinuity of early deposited geological units and mineral provinces;
- provide a series of geological constraints that require further investigation of the well established concept of São Francisco Craton and its peripheral fold belts.

CONCLUSIONS

Two major phases of crustal shortening have been described in the São Francisco — Borborema continental area. The former produced a thrust-belt convergence, with the main tectonic events occurring between 2.2 and 1.9 Ga. During this phase, gold mineralization in the Middle Rio Itapicuru Gold Province, was formed. Mantle upwelling following the post-orogenic extensional collapse caused crustal melting, accompanied by intrusion of S-type granitic plutons, and magma extraction from the upper mantle. The gold mineralization origin in Serra de Jacobina is related to this event. The second phase was characterized by ubiquitous collisional tectonics related to the assembly of West Gondwana. Following this phase, a superplume activity occurred, which is responsible for hydrothermal gold deposits in the Western Chapada Diamantina. The metallogenetic analysis of this region allows to conjecture that metallotects operated with great intensity during the Proterozoic and they were recycled during the Cambrian thermotectonic event, with enough mineralizing potential to form IOCG deposits. Some of these deposits may contain large volumes of mineralized rocks of Olympic Dam type (Cu-U-Au-REE systems), which were protected from erosion by the younger sedimentary cover.

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