GR Focus

Supercontinent evolution and the Proterozoic metallogeny of South America

João Batista Guimarães Teixeira ^{a,*}, Aroldo Misi ^a, Maria da Glória da Silva ^{a,b}^a Grupo de Metalogênese, Centro de Pesquisa em Geofísica e Geologia, Universidade Federal da Bahia, Campus Universitário de Ondina, Sala 201-C, Salvador; 40170-290, Bahia, Brazil^b Geological Survey of Brazil (CPRM)-Av. Pasteur, 404, Urca, Rio de Janeiro, 22290-240, Rio de Janeiro, Brazil

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Abstract

The cratonic blocks of South America have been accreted from 2.2 to 1.9 Ga, and all of these blocks have been previously involved in the assembly and breakup of the Paleoproterozoic Atlantica, the Mesoproterozoic to Neoproterozoic Rodinia, and the Neoproterozoic to Phanerozoic West Gondwana continents. Several mineralization phases have sequentially taken place during Atlantica evolution, involving Au, U, Cr, W, and Sn. During Rodinia assembly and breakup and Gondwana formation, the crust-dominated metallogenic processes have been overriding, responsible for several mineral deposits, including Au, Pd, Sn, Ni, Cu, Zn, Mn, Fe, Pb, U, P₂O₅, Ta, W, Li, Be and precious stones. During Rodinia breakup, epicontinental carbonate-siliciclastic basins were deposited, which host important non-ferrous base metal deposits of Cu–Co and Pb–Zn–Ag in Africa and South America. Isotope Pb–Pb analyses of sulfides from the non-ferrous deposits unambiguously indicate an upper crustal source for the metals. A genetic model for these deposits involves extensional faults driving the circulation of hydrothermal mineralizing fluids from the Archean/Paleoproterozoic basement to the Neoproterozoic sedimentary cover. These relations demonstrate the individuality of metal associations of every sediment-hosted Neoproterozoic base-metal deposit of West Gondwana has been highly influenced by the mineralogical and chemical composition of the underlying igneous and metaigneous rocks.

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* Corresponding author. Tel./fax: +55 71 3203 8501.

E-mail address: jbgteixeira@gmail.com (J.B.G. Teixeira).

1. Introduction

Four major lithotectonic domains overlie the South American Plate: the South American Platform, the Andean Mountain Belt and the Patagonian Massif to the west, and the Atlantic oceanic crust to the east.

Investigations on geochronology of the South American Platform (Fig. 1a), based on the interpretation of Nd isotope systematics allowed Sato and Siga Júnior (2000) to conclude that while large volumes of Archean terranes are preserved (35%), massive amounts of juvenile crust have been accreted during the Paleoproterozoic (54%), mainly from 2.2 to 1.9 Ga. The platform has been completed through the addition of Meso- to Neoproterozoic material (10%), together with a small fraction (1%) of Phanerozoic igneous rocks (Fig. 1b).

It is well documented that all the cratonic blocks of South America have been involved in the assembly and breakup of supercontinents and large landmasses, such as Atlantica in the Paleo- to Mesoproterozoic (e.g., [Condie, 2002](#); Rodinia in the Mesoproterozoic (e.g., [Cordani et al., 2000](#)) and West Gondwana, in the Neoproterozoic to Phanerozoic (e.g., [Unrug, 1996](#)).

We completed this study as part of the UNESCO/IGCP 450 Project entitled “Proterozoic Sediment-hosted Base Metal

Deposits of Western Gondwana” (2000–2005). One of the most enigmatic issues that induced the proposal of the IGCP 450 project is the remarkable difference between the Proterozoic sediment-hosted base metal deposits of West Gondwana in both sides of the Atlantic. Although similar Neoproterozoic stratigraphic sequences host the deposits and comparable extensional processes would be involved in their formation, no Cu–Co mineralizations are found in the South American equivalent units. A related subject has been discussed by [De Wit et al. \(1999\)](#), based on the interpretation of the ore deposit database for the Gondwana. These authors demonstrated that the majority of the Gondwana’s metal deposits are unevenly distributed in time and space and that a greater incidence of tin and tungsten mineralizations exists in the West Gondwana crust, in contrast to the East Gondwana, where these metals are comparatively rare.

In this paper we place the Proterozoic mineralization processes of South America into a global tectonic and temporal framework. First, we provide evidence to account for the high production of juvenile crust within the 2.2–1.9 Ga interval in the South American Platform, and discuss the connection between the Paleoproterozoic crust formation with the associated, mantle-dominated metallogenic processes. Subsequently, we outline toward the younger paleocontinent evolution, which

Fig. 1. (a) The cratonic blocks of the South American Platform. Modified after [Cordani et al. \(2000\)](#). (b) Cumulative curve of continental growth for the South American Platform, based on the Nd systematics. After [Sato and Siga Jr. \(2000\)](#).

comprises Rodinia assembly and breakup, in conjunction with Gondwana formation, and their relationships with the crust-dominated, Meso- to Neoproterozoic metallogenic processes.

In summary, we propose a new configuration for the Atlantica paleocontinent, which explains the contrasting Proterozoic sediment hosted deposits and also documents the Neoproterozoic history of West Gondwana and its mineral deposits.

2. Supercontinent Columbia and the configuration of Atlantica

According to Rogers (1996), two main Paleoproterozoic landmasses existed: Arctica (including Laurentia, Siberia, Baltica, North Australia and North China), and Atlantica (containing Amazonia, Congo, West Africa, and Rio de la Plata). A supercontinent named Columbia, which survived from approximately 1.8 to 1.5 Ga, has been proposed by Rogers and Santosh (2002). Subsequently, Zhao et al. (2002, 2004) provided a review of supercontinents including Columbia between 2.1 and 1.8 Ga (Fig. 2).

Due to the lack of reliable paleomagnetic data, the most robust evidence for early supercontinents comes from precise dating of collisional orogens and the correlation of these orogens between cratons. Following this principle, the geological background of the Paleoproterozoic Atlantica continent has been outlined (e.g., Teixeira and Misi, 2003; Heilbron et al., 2003).

The new configuration for Atlantica, as proposed in this paper includes the majority of Precambrian provinces belonging to the present-day South American continent, namely Amazon, São Francisco, Rio de La Plata and Borborema, along with the West African Craton and the Yilgarn and Pilbara blocks of

Western Australia (Fig. 3). Here the great Paleoproterozoic orogenic belts come into view, established by the presumed root zones of collisional mountain chains. A likely configuration for Atlantica at the outside edge of the Columbia supercontinent is shown in Fig. 2.

Peculiar features of Atlantica were the Birrimian and Transamazonian greenstone belts (2.2–2.1 Ga), composed of earlier erupted Fe-rich MORB-type tholeiite and later erupted island arc andesite, associated with epiclastic and siliciclastic sediments. Most of these greenstone belts and accompanying intrusive granitoids are dislocated above gneiss-migmatite basement of the Guyana Shield and of the São Francisco, São Luís and West African cratons.

Insertion of the Western Australian blocks in the Atlantica context is based on the hypothesis that the large iron deposits of the Hamersley Basin together with those from Venezuela (Imataca Complex), and others from Brazil (Quadrilátero Ferrífero, Itabira, and Guanhanes) were part of the same basin, which evolved between 2.52 and 2.42 Ga (e.g., Babinski et al., 1993). It deserves mentioning that the Serra dos Carajás Basin in northern Brazil is older. It contains the world's largest iron ore reserve (18 billion tons of hematite), and has been deposited between 2.75 and 2.74 Ga (Trendall et al., 1998).

3. Wilson cycle in Atlantica and related metallogeny

The present hypothesis for Atlantica evolution contemplates all the steps of a Paleoproterozoic Wilson Cycle, whose completion incorporated the tectonic and metallogenic processes associated with the development of a mantle superplume. Several mineralization phases sequentially took place, every one unequivocally associated with a discrete stage of mantle–crust interaction (Fig. 4).

Fig. 2. Reconstruction of the Paleoproterozoic supercontinents Columbia and Atlantica. Modified after Zhao et al. (2002, 2004). Thick black lines represent the Paleoproterozoic collision belts (ages are labeled). White lines appear at the borders of the Atlantica components.

3.1. The oceanic stage (Steps 1 and 2 in Fig. 4)

This phase involved extensive basaltic magmatism, which was probably already active 2.5 Ga ago. The bulk of the flows is made of Fe-rich MORB-tholeiite (Silva et al., 2001). Subduction (Step 2 in Fig. 4) started about 2.17 Ga, and gave rise to restricted calc-alkaline volcanic centers that were associated with massive tonalite plutonism. Mafic and felsic volcanic rocks associated with clastic sediments and granitoid intrusions make up the Birrimian greenstone belts in West Africa (Oberthür et al., 1994), and the Transamazonian greenstone belts present in the Guyana Shield (Voicu et al., 2001) and in the São Francisco Craton (Silva et al., 2001).

The only known mineralization that theoretically could be syngenetic and possibly associated with the volcanosedimentary sequences of the paleoproterozoic greenstone belts is the highly metamorphosed Caraíba deposit, Curaçá Valley, Bahia, Brazil. This is an unusual, strongly deformed copper deposit, with predominance of bornite in excess of chalcopyrite, hosted in dioritic rocks (Maier and Barnes, 1999). The host rocks crystallized at ca. 2580 Ma, and were metamorphosed to the granulite facies at ca. 2103 Ma (Oliveira et al., 2004).

3.2. Ocean closure (Step 3 in Fig. 4)

This stage took place from 2.1 to 2.0 Ga, followed by continental collision and orogenesis. The 4500 km long

granulite-granitoid belt that extends from Argentina (Tandilia) towards Uruguay (Piedra Alta), southern and southeastern Brazil (Encantadas, Luiz Alves, Mantiqueira, Guanhões, Juiz de Fora), Venezuela (Imataca), Guyana (Central Guyana), north-eastern Brazil (Jequié, Itabuna, Salvador-Curaçá), and reaches Liberia and Ivory Coast (Kenema-Man) is part of the large root zone of the presumed mountain chain (Fig. 3). It is worth bearing in mind that some of the terranes in this root zone have been earlier subjected to Archean high-grade metamorphism, such as the Jequié Block in the São Francisco Craton, Bahia, Brazil (Barbosa and Sabaté, 2004) and the Imataca Complex, Amazon Craton, Venezuela (Sidder and Mendoza, 1995). 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 and Tyler, 2004) are thought to have been connected with this major high-grade belt (see Fig. 3).

Syn-collisional, orogenic-type gold deposits (Teixeira et al., 2002) are found in Fazenda Brasileiro, Rio Itapicuru greenstone belt (Serrinha Block), São Francisco Craton (Silva et al., 2001), in Omai, Barama-Mazaruni greenstone belt, Guyana Shield (Norcross et al., 2000), and in the Tapajós-Parima orogenic belt, northern Brazil, Venezuela and Guyana (Santos et al., 2001).

Fazenda Brasileiro has been an important hard-rock gold producer in Bahia, Brazil (53 t gold since 1984). The orebodies are at the borders of a 10 km long differentiated sill (the Weber Belt), which intrudes the contact zone between tholeiite

Fig. 3. Reconstruction of the Atlantica paleocontinent by ca. 1.85 Ga. Source of geological data: Amazon (Tassinari et al., 2000); Guyana (Voicu et al., 2001); São Francisco; Barbosa and Sabaté, 2004); West Africa (Milesi, 1989); Borborema (Fetter et al., 2000); Western Australia (Cawood and Tyler, 2004).

metabasalts and intermediate calc-alkaline metavolcanics. The main host to the mineralization is a quartz-chlorite-magnetite schist, which results from the deformation and hydrothermal alteration of a ferrogabbroic protolith. Gold occurs as free fine-grained particles (<20 μm), or accompanied by sulfides (arsenopyrite, pyrrhotite and pyrite) in quartz-carbonate-albite veins and in their alteration haloes (Teixeira et al., 1990).

The Omai deposit, the largest gold producer operating in the Guyana Shield, consists of an intrusion-related vein system. Gold occurs as free grains hosted largely by quartz veins disseminated throughout the main body of a dioritic intrusion. The gold vein stockwork consists mainly of quartz, ferroan carbonate, sulfides and scheelite, ranging in size from stringers up to 5 cm in width to occasional larger veins (Norcross et al., 2000).

The Tapajós-Parima orogenic belt is mainly composed of a back-arc sequence associated with several volcanic-plutonic terrains. The orogenic gold occurs as disseminated ores and in pyrite-quartz-carbonate veins hosted by metamorphic rocks and granitoids including the 2010 Ma old metabasalts, meta-andesites and tonalites of the Cuiú-Cuiú Complex and the 1974–1957 Ma old calc-alkaline monzogranites and granodiorites of the Creporizão Suite (Santos et al., 2001).

Post-collisional chromite mineralization occurs in the Jacurici Valley district, Bahia, Brazil, hosted by a differentiated mafic-ultramafic sill, which crystallized around 2085 Ma (Oliveira et al., 2004). The mafic-ultramafic intrusions of the Jacurici Complex were emplaced into the Archean/Paleoproterozoic granulite terrane of the Caraíba complex. The intrusions are distributed along a north-south 70 km long belt. The Ipueira-Medrado sill is a single intrusion that has been tectonically disrupted by faulting and folding into two segments that occur on the limbs of a synform. It is conformable with the enclosing quartzofeldspathic gneisses, which include serpentine-bearing marble, calcsilicate rocks and metachert. The sill is composed mainly of dunite, harzburgite and pyroxenite. The ore in the Ipueira-Medrado Sill is mined from a single, 5–8 m thick chromitite layer, which is continuous but structurally disrupted, within the 300 m thick sequence of cumulate rocks (Marques and Ferreira Filho, 2003).

3.3. Mantle upwelling (Step 4 in Fig. 4)

This stage has started at around 1.9 Ga, following the post-orogenic extensional collapse. A straight consequence of this phenomenon was crustal melting together with intrusion of S-type granite plutons, and magma extraction from the upper mantle, which produced the elongated peridotite intrusion in the Serra da Jacobina region, São Francisco Craton, Bahia, Brazil. Gold and emerald mineralizations were associated with the emplacement and cooling of these anatectic magmas (Teixeira et al., 2001).

The gold deposits in the Serra de Jacobina region (Bahia) are in a belt of siliciclastic metasedimentary rocks intercalated with mafic and ultramafic rocks and underlain by a tonalite-trondhjemite-granodiorite gneiss-dominated (TTG) basement. The majority of the gold occurrences are hosted by quartz-pebble conglomerates, and resembles placer-type deposits.

However, structurally controlled hydrothermal orebodies, and the occurrence of gold also in quartzites and mafic and ultramafic rocks, support an epigenetic model for the mineralizing events. Gold mineralization in Jacobina is interpreted to be an integral part of the 1.9 Ga tectonothermal evolution of the region (Teixeira et al., 2001).

The emeralds of Carnaíba and Socotó, in the Serra de Jacobina, are mainly in phlogopite-schist bands that were formed by metasomatic reaction between aplopegmatites and serpentinites (greisenization). Molybdenite and scheelite are associated minerals. The beryl mineralization is in the metamorphic aureole of 1.9 Ga S-type granites, which intruded the Archean migmatite basement and also the quartzites of the Serra de Jacobina (Santana et al., 1995).

3.4. Rifting and continental breakup (Step 5 in Fig. 4)

The resulting tectonic processes in response to the important mantle plume activity included (i) the 1.88–1.76 Ga widespread continental volcanism, e.g., Maloquinha, Iriri, Crepori and Teles Pires in northern Brazil (Santos et al., 2001); (ii) the Rio dos Remédios Group in Bahia; (iii) the Conceição do Mato Dentro felsic volcanic rocks, besides the later emplaced mafic dike swarms in Minas Gerais (Silva et al., 1995) and Bahia; (iv) the rift-related granites and felsic volcanic rocks in Goiás (Pimentel and Botelho, 2001). These volcanic activities were associated with the development of extensional basins and deposition of intracratonic sedimentary sequences, e.g., Gorotire and Beneficente groups in northern Brazil, the Espinhaço Group in Bahia and Minas Gerais, central-east Brazil, and the Arai Group in central Brazil (Dardenne and Schobbenhaus, 2000; Pimentel and Botelho, 2001).

This is an important metallogenic phase in association with the emplacement of anorogenic granitoid plutons. Examples of some related mineralizations in Brazil are (i) gold in Rio de Contas (Bahia); (ii) gold in Tapajós (Pará) and Alta Floresta, Mato Grosso (Santos et al., 2001); (iii) gold-palladium in Itabira, Minas Gerais (Oliveira et al., 2001); (iv) copper-gold in Gameleira and Breves deposits, Serra dos Carajás, (Lindemayer et al., 2001; Pimentel et al., 2003); (v) cassiterite in Pitinga (Amazonas), and in the Goiás Tin Province (Marini and Botelho, 1986), and (vi) wolframite in Pedra Preta, Pará (Dardenne and Schobbenhaus, 2000). The gold-palladium-platinum mineralization of Serra Pelada, Pará (Cabral et al., 2002) is presumably related to this tectonic phase.

Gold in the Rio de Contas district, central Bahia, Brazil is in structurally controlled quartz veins, hosted by low-grade metamorphosed siltstone and sandstone of the Paraguaçu Group, besides continental metarhyolites and epiclastic meta-sedimentary rocks of the Rio dos Remédios Group. Gabbroic sills often appear inside the mineralized zones. Gold is mostly invisible, and occur in two main mineralization settings: hydrothermal alteration zones around the gabbro sills, in association with pyrite, and kaolinization zones with tourmaline, developed in the metasedimentary and metavolcanic rocks.

The Tapajós and the Alta Floresta domains make up the most important Paleoproterozoic gold province of northern Brazil, comprising two main primary gold deposit types: orogenic and

intrusion-related (Santos et al., 2001). The intrusion-related, quartz vein deposits of the Tapajós Province are characterized by quartz-pyrite veins in potassic granites, and disseminated gold in pyrite-rich, hydrothermally altered mafic dikes. Quartz stockworks appear in some deposits. Small amounts of chalcopyrite, galena and sphalerite occur in several of the deposits (Santos et al., 2001).

The Itabira district, in Minas Gerais, is the second most productive Brazilian iron ore district, following the Carajás Mineral Province in northern Brazil. In addition to iron, both gold and palladium have been extracted in the Cauê and Conceição iron mines of the Itabira district. The presence of free Pd-bearing gold grains, which are elongated parallel to an earlier developed foliation, allowed estimation of the timing of ore deposition in relation to the main deformation phase. U–Pb isochron ages of 1.83 ± 0.1 Ga for the Au–Pd mineralization are contemporaneous with the early Transamazonian phase of shearing and thrusting (Olivo et al., 1996).

The host rocks for the Gameleira Cu–Au mineralization in the Serra dos Carajás region (Pará, Brazil) are amphibole-

plagioclase-quartz rocks, biotite-quartz-garnet rocks, banded magnetite-quartz-grunerite rocks, iron formation, and quartz-rich rocks of the Salobo-Pojuca Group, of the Itacaiúnas Supergroup, formed in the time span of 2742–2732 Ma (Pimentel et al., 2003). These rocks are intersected by a 300–500 m thick gabbro sill. Banded, iron-rich rocks that occur preferably in the biotite-quartz sill contact exhibit clear evidence of hydrothermal origin. Mineralization is epigenetic, occurring in the banded iron-rich rocks and also in quartz veins, disseminated, filling foliation fissures, or forming the matrix of brecciated quartz veins. The main sulfides are chalcopyrite and bornite, with traces of cobaltite, cobalt pentlandite, pyrite, molybdenite and gold (Lindenmayer et al., 2001).

The Breves Cu–Au deposit, in the Serra de Carajás region, is hosted by sandstones and siltstones of the 2681 ± 5 Ma Águas Claras Formation (Trendall et al., 1998), in the roof zone of a complex, highly altered granite intrusion. Mineralization is disseminated in a greisenized zone, resulting from alteration of monzogranite and syenogranite. The ore-bearing greisen contains abundant xenomorphic quartz in association with Fe-

Fig. 4. The Paleoproterozoic Wilson Cycle and related metallogenic events in South America. The light gray area indicates the period of rapid crustal growth for the South American Platform (after Sato and Siga, 2000), which stands for the assembling of Atlantica. Modified after Teixeira and Misi, 2003. It is worth recalling that only the most important metallogenic events are listed.

chlorite and muscovite (Tallarico et al., 2004). Gangue assemblage includes fluorite, tourmaline, and minor amounts of monazite, xenotime, chlorapatite, thorite, zircon, calcite, siderite and bastnaesite. Copper mineralization is dominated by chalcopyrite associated with pyrite, arsenopyrite, pyrrhotite, and molybdenite. Gold particles together with native bismuth are common as inclusions in chalcopyrite. Results of SHRIMP II U–Pb in zircon, monazite and xenotime data from the Breves granites and veins that cut the greisenized granites place the age of Cu–Au–(W–Bi–Sn) mineralization at ca. 1.88–1.87 Ga, the major phase of emplacement of the A-type Paleoproterozoic granites in the Carajás Belt (Tallarico et al., 2004).

Tin mineralization in the Pitinga Province, Amazonas, is associated with the Paleoproterozoic (1.82 Ga) Madeira and Água Boa plutons. Primary mineralization occurs as disseminated cassiterite in the magmatic albite granite facies of the Madeira pluton, or as hydrothermal cassiterite, related with greisen and episyenites in the Água Boa pluton (Dardenne and Schobbenhaus, 2000).

The Pedra Preta wolframite deposit, in the Serra dos Carajás region (Pará), contains the most important tungsten concentration yet discovered in the Amazon Craton (Dardenne and Schobbenhaus, 2000). The wolframite occurs in a vein network system developed in the Musa anorogenic granite (1.88 Ga), which intrudes the Andorinhas greenstone belt (2.9 Ga). Mineralization is hosted in quartz veins, in a mineral assemblage of topaz, muscovite, tourmaline, pyrite, pyrrhotite and chalcopyrite (Dardenne and Schobbenhaus, 2000).

One of the greatest gold rush in Brazil took place at Serra Pelada, located in the northeastern sector of the Serra de Carajás region, Pará. During a 10-year period (1980–1990), more than 40 metric tons of gold have been manually extracted by a crowd of garimpeiros (which occasionally reached 40,000 workers) from a 130-m deep open pit. The Serra Pelada deposit is tectonically controlled, hosted by a folded anchimetamorphic, fluvial to shallow-marine sequence of the Neoproterozoic Águas Claras Formation that remain on a flat, tectonic contact above a thick dolomite sequence. The bonanza-type, Au–Pd–Pt mineralization is in the deeply weathered hinge zone of a recumbent syncline, associated with a tectonic breccia (Cabral et al., 2002). This breccia consists of angular fragments of sugary quartzite, quartz and gray siltstone, in a matrix of hematite and manganese oxides. The structural control together with the characteristic ore assemblage and an unusual Pd–Au average ratio strongly indicate a hydrothermal origin for the coarse-grained Pd-bearing gold nuggets in the near surface bonanza (Cabral et al., 2002), most probably connected with the cooling of the nearby A-type Cigano granite, which intruded around 1.88 Ga (Machado et al., 1991).

4. Assembly and breakup of Rodinia, assembly of West Gondwana, and related metallogeny

Geochronological and paleomagnetic data led some authors to believe in long-term intervals for the assembling and breakup of cratonic terrains during evolution of the Rodinia supercontinent (Fig. 5). Condie (2002) discussed the continental rifting and collisional events during the last 1000 Ma, based on

geochronological data from well-dated sites worldwide. He concluded that Rodinia formation took place between 1300 and 900 Ma, and that the continental breakup occurred between 950 and 600 Ma. This proposal implies that such events ought to be diachronic, along with the Pan African/Brasiliano orogenic cycle and Gondwana formation, in which the most important episodes are dated between 650 and 500 Ma. Fig. 6 summarizes the chronological evolution of Rodinia assembly and breakup, followed by assembly of West Gondwana, essentially based on the available geological and isotopic data. The events related to this evolution were responsible for some important metallogenic processes that formed a variety of economic mineral deposits in South America.

4.1. The pre-Rodinia growth of the Amazon Craton (Step 1 in Fig. 6)

This stage is recorded by the accretion of the Rio Negro-Juruena Province (Tassinari et al., 2000) to the western margin of the Paleoproterozoic Ventuari-Tapajós Province (see Fig. 1b for location), spanning the 1750–1500 Ma interval.

4.2. The Grenville orogeny in the Western Amazon Craton (Steps 2, 3 and 4 in Fig. 6)

The Grenville orogeny is recorded in the Amazon Craton by accretion of juvenile crust in two Mesoproterozoic tectonic episodes (Tassinari et al., 2000; Cordani et al., 2003): the Rondônia-San Ignacio belt (1550–1300 Ma), formed by mafic–ultramafic and volcanic rocks, and the Sunsás event (1300–1000 Ma), at the Brazil-Bolivia border, consisting of syn- to post-tectonic granitoids plus basaltic magmatism associated with meta-sedimentary sequences (Santos et al., 2001) (see Fig. 1b for location). These provinces host important gold deposits controlled by extensive shear zones related to the Sunsás event. The well-known tin province of Rondônia (1600–990 Ma) is associated to rapakivi granites formed during several magmatic pulses.

A radiating pattern of 1000 million-year-old tholeiitic dike swarms was described by Correa-Gomes and Oliveira (2000), which occur to both side of the Atlantic, in eastern South America (Bahia coastline) and western Africa (Cameroun and Congo). These mafic dikes were probably emplaced during a mantle upwelling event, which occurred in the last stage of Rodinia assembly (Figs. 5 and 6).

4.3. The breakup of Rodinia (Steps 5 and 6 in Fig. 6)

Rodinia breakup started near 950 Ma ago and continued until ca. 600 Ma (Condie, 2002). During the same time interval the first components of Gondwana started to collide, pointing toward the construction of a new supercontinent.

The Goiás Magmatic Arc in central-Brazil represents juvenile crust created during Neoproterozoic orogenic events. This unit was formed by accretion of island arc systems to the western margin of the São Francisco Craton within the 660–600 Ma interval (Pimentel and Fuck, 1992; Laux et al., 2005a). Much of

the magmatism ranges in composition from tonalite to granodiorite and is exposed between narrow volcanosedimentary belts. Some of the radiometric data obtained from gneiss are U–Pb zircon ages of 899 ± 7 Ma and whole-rock Rb/Sr ages of 818 ± 57 Ma, with Sr initial ratio of 0.7042 (Pimentel et al., 2000). Large granite plutons and small mafic–ultramafic layered complexes represent the last magmatic events, which occurred from 670 to 590 Ma.

Niqueliferous laterite deposits developed above Ni-bearing peridotites in the Niquelândia and Barro Alto complexes, Goiás, Brazil (Dardenne and Schobbenhaus, 2000). Several small gold deposits are associated with hydrothermal alteration zones in tonalite to diorite gneisses. In addition, there are the Cu–Au deposits of Chapada, which are interpreted as volcanogenic exhalative or porphyry-copper type (Dardenne and Schobbenhaus, 2000).

Widespread records of Rodinia breakup in South America and Africa are the epicontinental and passive margin-type Neoproterozoic basins, which evolved as a consequence of extensional events (Misi, 2001; Misi et al., 2005). Except for a few small Neoproterozoic basins formed in tectonically active fold belts (e.g. the Dom Feliciano Belt in southern Brazil), where related volcano-plutonic magmatic events give ages of 594 ± 5 Ma (U–Pb SHRIMP in zircon; Remus et al., 2000), there are no datable volcanic beds associated with the

sedimentary rocks in the epicontinental and passive margin basins of South America. Notwithstanding in Africa, Sturtian diamictites of the Chuos Formation, at the base of the Neoproterozoic carbonate-siliciclastic successions of Namibia, and possible equivalent of the diamictites at the base of the Bambuí Group and correlate sequences in Brazil, were dated 746 ± 2 Ma (U–Pb, SHRIMP, Kaufman et al., 1997). In the absence of volcanics, Babinski and Kaufman (2003) obtained an 11-point Pb–Pb isochron from well-preserved carbonates of the Bambuí Group, indicating a possible depositional age of 740 ± 22 Ma. A younger carbonate succession of presumed Marinoan age (600–575 Ma) occurs above Varanger diamictites (610–600 Ma) in the southeastern border of the Amazon Craton, Brazil, as well as in Uruguay and Argentina. Both Sturtian and Marinoan glacial diamictites in South America are overlain by carbonates with negative $\delta^{13}\text{C}$ excursions (Misi et al., 1999; Misi, 2001).

The Neoproterozoic Vazante Group (Minas Gerais, Brazil) hosts the largest Zn–Pb deposits of South America. The Morro Agudo and the Vazante mines, along with several minor deposits are in dolomitic rocks of passive margin carbonate-siliciclastic successions. The two mines have been continuously exploited during the last 15 years. Vazante is producing 0.8 Mt/year of ROM ore with 13.5% Zn, while Morro Agudo produces 0.8 Mt/year of ROM ore with 5% Zn and 2% Pb. Ore reserves in these deposits

Fig. 5. Reconstruction of the Rodinia supercontinent by ca. 1000 Ma. Modified after Dalziel et al. (2000) and Loewy et al. (2003).

are 18 Mt at 23% Zn in Vazante, and 8 Mt at 6.3% Zn and 2.2% Pb in Morro Agudo (geologist Flávio Tolentino Oliveira, Companhia Mineira de Metais, personal communication).

Misi et al. (2000, 2005) concluded that the Paleoproterozoic basement rocks are the sources of metals in these deposits and that most of the sulfur is derived from seawater. The same authors demonstrated that the Zn–Pb deposits and occurrences of the Vazante and Bambuí Groups are undoubtedly associated with fault zones and partially associated with evaporitic facies of the Sturtian carbonate sequences. Based on the geological, fluid inclusion, and Pb and S isotope data, the authors proposed a model involving fluid movement in a hydrothermal system, carrying metals from the Paleoproterozoic granite-gneiss basement along normal faults, which remained active during deposition of the carbonate-siliciclastic sequence.

Phosphate deposits are hosted by carbonates overlying the Sturtian (Da Rocha Araújo et al., 1992; Misi and Kyle, 1994)

and Varanger diamictites. Commercial phosphate concentrate is produced in two separate districts, one in Bahia (Irecê), another in Minas Gerais (Rocinha-Lagamar). The Irecê phosphorite, in the carbonate platform sequences of the Una Group (equivalent to the Bambuí Group), is mainly hosted by columnar stromatolitic structures (within dolomitic rocks), which were classified as *Jurusanian krilov* (Srivastava, 1982). The origin of the phosphorite beds may be related to bacterial degradation of organic matter in the cyanobacterial mats that “...probably was responsible for local phosphate enrichment of the pore waters, followed by precipitation of carbonate fluorapatite or by replacement of early carbonate cements” (Misi and Kyle, 1994). The Rocinha phosphorite, in the Vazante Group, is the most important sedimentary phosphate deposit in Brazil. It is associated with glauconitic and phosphate schists and phosphorization was interpreted to be associated with chemical precipitation (Da Rocha Araújo et al., 1992).

Fig. 6. Sequence of the Meso- to Neoproterozoic geotectonic events in the South American Platform and related metallogenic events. It is worth recalling that only the most important metallogenic events are listed.

Iron and manganese concentrations in the Urucum district, Brazil, are associated with the Varanger-Marinoan carbonates of the Corumbá Group.

Economic iron deposits also occur in Porteirinha, Minas Gerais, associated with exhalative sediments of the Macaúbas Group, which have been deposited in a Neoproterozoic rift basin (Dardenne and Schobbenhaus, 2000).

The Riacho dos Machados gold deposit (nowadays exhausted) is hosted by a shear zone of Brasiliano age that affected a Paleoproterozoic volcanosedimentary sequence, which makes up the substratum of the Araçuaí Belt (Dardenne and Schobbenhaus, 2000).

The Pb–Zn–Ag–Ba deposits of the Ribeira Belt at the border of São Paulo and Paraná are venular and either stratiform or strata-bound, hosted by Meso- to Neoproterozoic calcsilicate and carbonate metasediments associated with felsic volcanic tuffs and intruded by Neoproterozoic to Lower Paleozoic granites (Dardenne and Schobbenhaus, 2000). The Perau and Canoas deposits are composed of massive and disseminated sulfides (mainly galena, sphalerite, chalcopryrite, pyrite and pyrrhotite), and have been

interpreted as sedimentary-exhalative, or SEDEX-type (Daitx, 1998). The Panelas Pb–Zn–Ag deposits are characterized by discordant veins of massive galena, sphalerite and pyrite with scarce quartz and calcite gangue within carbonate rocks (dolomite and limestone) of the Neoproterozoic Açungui Group.

4.4. The assembly of West Gondwana (Steps 7, 8 and 9 in Fig. 6)

Assembling of the continental blocks of West Gondwana started around 900–700 Ma interval, with final amalgamation of the whole Gondwana around 550–530 Ma, based on paleomagnetic, geologic and isotopic data (Meert, 2001).

A sequence of geodynamic and tectonothermal events that occurred from ca. 600 to 510 Ma in the African continental area and adjacent Gondwana terranes are broadly referred to as the Pan-African Cycle, or the Brasiliano Cycle in South America (Figs. 7 and 8).

West and East Gondwana have been the latest large landmasses, which remained tectonically stable within Pangea,

BRASILIANO BELTS

- 1- Borborema
- 2- Araguaia
- 3- Paraguay
- 4- Brasília
- 5- Rio Preto
- 6- Sergipano
- 7- Araçuaí
- 8- Ribeira
- 9- Dom Feliciano

Fig. 7. The Pan-African/Brasiliano orogenic belts (600–400 Ma). Sources: South America (Cordani et al., 2003), Africa (Goodwin, 1996).

The last phase of West Gondwana assembling in South America is characterized by ubiquitous collisional tectonics, which produced a variety of mineral deposits and occurrences in Brazil and Uruguay, as commented below.

Vazante, Morro Agudo, etc. (Brazil)

Fig. 9. Plot of $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ for some Neoproterozoic sedimentary hosted sulfide deposits of Africa and Brazil. Source: Cunha et al. (2003), Kamona et al. (1999), Frimmel et al. (2004), and Burnard et al. (1993). UC=upper crust evolution curve after Zartman and Doe (1981).

Table 1
Some characteristics of the Neoproterozoic base metal deposits of Africa (a) and South America (b)

Name	Country	Commod.	Other elements	Type	Tectonic setting	Control
<i>(a) Africa</i>						
Tsumeb	Namibia	Cu–(Pb)–(Zn)	Ag–As–Ge–Ga–Cd	M	Intracratonic rift basin	Fault
Berg Aukas	Namibia	Zn–Pb–(Cu)	As–Ag–Ge–Ga–Cd–Fe–Mn	M	Intracratonic rift basin	Fault
Rosh Pinah	Namibia	Zn–Pb–(Cu)–(Ag)		M	Rift basin	Fault
Skorpion	Namibia	Zn (willemite)	Si	M	Rift basin	Stratigraphy
Kabwe	Zambia	Pb–Zn–(Ag)–(Cd)	Fe–Cu–Ge–V	M	Intracratonic rift basin	Fault
Nampundwe	Zambia	Cu–S	Fe–Zn	M	Intracratonic rift basin	Stratigraphy
Baluba	Zambia	Cu–Co	Fe–Zn	BM	Intracratonic rift basin	Fault
Konkola						Fault
Nchanga						Stratigraphy
Nkana						
Mufulira						
Kolwezi	Congo DR	Cu–Co–(U)	Fe–Zn	BM	Intracratonic rift basin	Fault
Kambove						Stratigraphy
Likasi						
Kakanda						
Fungurume						
Kipushi	Congo DR	Cu–Pb–Zn		M	Intracratonic rift basin	Fault
<i>(b) South America</i>						
Morro Agudo	Brazil	Zn–Pb	Fe–Ba	M	Passive margin rift basin	Fault
Vazante	Brazil	Zn (willemite)	Si–Pb–Fe–Cd–Ag–V–U–Co–As–Sb–Cu–Ni	BM	Passive margin rift basin	Stratigraphy
Fagundes	Brazil	Zn–Pb	Fe–Cd–Ag–Co–As–Au–Sb–Cu–Ni–Hg–Mo	D	Passive margin rift basin	Fault
Ambrosia	Brazil	Zn–Pb	Fe–Cd–Ag–V–U–Co–Mo–Au–Sb–Cu–Ni	D	Passive margin rift basin	Stratigraphy
Nova Redenção	Brazil	Pb–(Zn)	Fe–Ba	D	Intracratonic rift basin	Fault
Irecê	Brazil	Zn–Pb	Fe–Ag–Ba–Cd–P	D	Intracratonic rift basin	Stratigraphy
São Francisco Basin (several)	Brazil	Pb–Zn–F	Fe–Ba	D	Intracratonic rift basin	Fault
Camaquã (several)	Brazil	Cu–Au	Fe–Zn–Pb–Ba	D	Molasse deposits in orogenic belt	Stratigraphy
Santa Maria	Brazil	Pb–Zn–(Cu)–(Ag)	Fe–Ba	D	Molasse deposits in orogenic belt	Fault
Lavras do Sul (several)	Brazil	Au–(Cu)–(Pb)–(Zn)–(Ag)	Fe	D	Molasse deposits in orogenic belt	Fault
Canoas	Brazil	Pb–Zn–(Cu)	Fe–Ba	D	Rift basin	Fault
Panelas (several)	Brazil	Pb–Zn–Ag	Sb–As–Fe–Au–F	D	Rift basin	Fault
Perau	Brazil	Pb–Zn–Ag–(Cu)	Fe–Ba	D	Rift basin	Fault
Lavalleja (several)	Uruguay	Cu–(Mo)–(Pb)–(Zn)		D	Back-arc (?) rift basin	Fault (?)

Notice that although similar tectonic setting and ore controls are observed in both continents, different metal associations stand out among deposits. Type of deposit: M=mine; BM=world-class mine (>5 Mt of metal reserves); D=deposit (closed mine or non-economical reserve).

of the Vazante and Bambuí groups, is recorded at ca. 630 Ma (Dardenne and Schobbenhaus, 2000). Many gold deposits and occurrences are associated with these fault zones.

The Morro do Ouro gold deposit (Paracatu, Minas Gerais) is a low-grade-large tonnage deposit hosted in carbonaceous phyllite that overthrusts the rocks of the Vazante Group in the external zone of the Brasília Fold Belt. The Crixás gold deposit, one of the most important primary deposits of Brazil is made of quartz veins hosted in carbonaceous schist, associated with a low-angle shear zone probably related to the Brasiliano event (Dardenne and Schobbenhaus, 2000).

An important tectono-thermal event with companion granite plutonism, which took place at ca. 580 Ma, was recognized in the Borborema Province. Two important mineralization types are connected with this event: the Itaitia U-deposit, in northern Ceará, associated with a Neoproterozoic episyenite intrusion, which produced a sodic metasomatic aureole in the host gneiss, and the Seridó Scheelite Province (Rio Grande do Norte and Paraíba), which has been intensely mined for tungsten since the Second World War. The ore is hosted in skarn deposits, generally located in the marble/granite contact (Dardenne and Schobbenhaus, 2000).

Disseminated and vein type Au–Cu–Pb–Zn–Ag mineralizations, interpreted as porphyry-gold deposits, occur in the Lavras do Sul granite complex (610–580 Ma), of shoshonitic to alkaline affinity, in the State of Rio Grande do Sul, Brazil. The orebodies are always associated with breccias of hydrothermal origin, which occur in fault and shear zones (Dardenne and Schobbenhaus, 2000).

The Camaquã copper mine in Rio Grande do Sul has been the main source of copper in Brazil for approximately 100 years (until 1996). The orebodies consist of veins, stockworks and disseminations of copper sulfides, hosted by sandstone and conglomerate of the Neoproterozoic to Early Paleozoic Camaquã Basin (Laux et al., 2005b). Recent Pb–Pb isotopic systematics applied to the Camaquã sulfides allied to U–Pb geochronological results for the main granite intrusions have constrained the age of mineralization to the period of 590–560 Ma ago (Remus et al., 2000). These recent data indicate that the Camaquã Mine sulfides are related to a distal hydrothermal-magmatic system associated with granite emplacement, during the collision of the Rio de la Plata and the Kalahari cratons (Laux et al., 2005b).

The final tectonic event related to the assembling of West Gondwana in South America has been the extensional collapse of orogenically thickened crust. The extensive pressure relief due to this process led to the production of voluminous, post-collisional granites in the Araçuaí Belt, eastern Brazil (Whittington et al., 2002).

Hydrothermal activity associated with the cooling of younger S-type granites, during rapid exhumation of the orogen between 520 and 500 Ma, created the Eastern Pegmatite Province of Brazil at the boundary of the States of Minas Gerais and Bahia. This is one of the largest and well renowned pegmatite provinces of the world, because of the gem-quality of its mineral specimens, which include emerald, aquamarine, tourmaline, alexandrite, amethyst, citrine and topaz.

Another large granitic pegmatite province in Brazil is the Seridó Province, associated with supracrustal rocks of the Borborema Province, at the border of Rio Grande do Norte and Paraíba states. These pegmatites are essentially composed of muscovite, quartz and microcline, with a variable degree of albitization. The younger suite of the Seridó pegmatites is 510–450 Ma old, and genetically related to late-tectonic Brasileiro granites. From the Second World War until now, the Seridó Pegmatite Province has produced huge amounts of valuable minerals such as beryl, columbite-tantalite, cassiterite, spodumene and many others.

5. Discussion and conclusions

Application of accurate correlation criteria has enabled us to reconstruct the shape of the Atlantica paleocontinent within the framework of the Paleo- to Mesoproterozoic Columbia Supercontinent (Fig. 2). The best explored global correlation elements have been (i) the Birrimian and Transamazonian (2200–2100 Ma) tholeiitic magmatism, which represents the oceanic phase of a Paleoproterozoic Wilson Cycle; (ii) the granulite-granitoid remnants of large orogenic belts, which represent the collision phase of the same Wilson Cycle; and (iii) the mineral deposits, which stand for the metallogenic products of some broad tectonothermal phases.

Most of the crustal components of the South American Platform were part of Atlantica, which grew at faster rates during the collision-related arc magmatism followed by mantle upwelling, within the 2100–1900 Ma time span (see Figs. 1c and 4). Some tectonic and metallogenic processes of great significance that have been related with the collision event were:

- The overthrusting of thickened beds of iron formation and associated granite-greenstone terrains of Western Australia above the southeastern edge of the São Francisco Craton, Minas Gerais, Brazil (e.g. Alkmim and Marshak, 1998) and above the northwestern sector of the Guyana Shield (Venezuela). Later, after continental breakup and reorganization, this large Archean basin was separated into four main allochthonous parts that now belong to (i) the Pilbara Block, Western Australia (Hamersley Basin); (ii) the Imataca Complex, Venezuela (Cerro Bolívar Iron district); (iii) the Araçuaí Belt, Minas Gerais, Brazil (Guanhães and Itabira Iron districts); and (iv) to the São Francisco Craton, Minas Gerais, Brazil (Quadrilátero Ferrífero iron district) (see Fig. 3 for location).
- The development of a large number of syn-collisional, orogenic gold deposits in the following contexts: Amazon Craton (e.g. Parima Domain, Venezuela and Guyana; Uaimiri Domain, Amazonas, Brazil; Tapajós Domain, Pará, Brazil; Alta Floresta Domain, Mato Grosso, Brazil); São Francisco Craton (e.g. Rio Itapicuru greenstone belt Bahia, Brazil), and Guyana Shield (e.g., Omai, Guyana).
- The generation of a few post-collisional orogenic gold deposits and beryl deposits in the São Francisco Craton (e.g., Serra de Jacobina, Bahia, Brazil).

After collision tectonics, and following the episode of orogenic collapse and mantle upwelling, a superplume event took place, which caused rifting, widespread continental volcanism and the emplacement of A-type granites within the 1880–1760 Ma interval. The ultimate result of this episode was the breakup of Atlantica, which was fragmented into three main portions: the Western Australia, the Rio de la Plata–São Francisco, and the Amazon–(Guyana)–West Africa blocks. This is a highly productive metallogenic phase in South America, which resulted in a variety of gold, copper, palladium, uranium, tungsten and tin mineralization. The most important plume-related mineral deposits (e.g., the U-mineralization in Lagoa Real, São Francisco Craton, and the Sn-mineralization in Pitinga, Amazon Craton) were typically generated by hydrothermal activity developed at the metasomatic aureole of the anorogenic granites.

Following the Paleoproterozoic megaplume event, the Grenvillian orogeny testified a new continental assembling that resulted in the construction of the Rodinia supercontinent. This Mesoproterozoic orogenic phase and its related metallogenic events and products, however, are not well documented in South America.

On the other hand, the extensional event, which resulted in the breakup of Rodinia, characterized a very important metallogenic epoch during the Neoproterozoic era. The most important non-

ferrous base metal deposits (Cu–Co and Pb–Zn–Ag), now being exploited in Africa and South America, evolved mainly as a consequence of these extensional events, which originated the sedimentary basins and the carbonate-siliciclastic successions that host the mineral deposits. In fact, Pb–Pb isotope data of sulfides from these deposits either in South America or in Africa (Fig. 9), unambiguously indicate an upper crustal source for the metals (Burnard et al., 1993; Kamona et al., 1999; Misi et al., 2000, 2004; Frimmel et al., 2004; Misi et al., 2005).

For most of the South American and African base metal deposits, a genetic model comprised of extensional faults allowing the circulation of hydrothermal mineralizing fluids carrying metals from the Archean/Paleoproterozoic basement to the Neoproterozoic sedimentary cover is largely acceptable (Misi et al., 2000; Frimmel et al., 2004; Misi et al., 2005). Therefore, we can hypothesize that the individuality of the metal associations of each sediment-hosted Neoproterozoic base-metal deposit of West Gondwana has been highly influenced by the mineralogical and chemical composition of the underlying igneous and metaigneous rocks.

If this is a suitable hypothesis, the proposed arrangement of the South American continental blocks during the Paleoproterozoic era, as shown in Figs. 2 and 3 could possibly elucidate the basic enigma posed by the IGCP 450 project, that is: “Why Cu–Co deposits have not yet been discovered in the large Neoproterozoic sedimentary basins of South America?”.

Even for Pb–Zn deposits in these basins, hosted by equivalent carbonate-siliciclastic successions, there is a considerable difference in metal association, as shown in Table 1. In agreement with our point of view, any acceptable explanation should rely on the statement that the Archean/Paleoproterozoic basement rocks of South America and Africa (except for the West Africa craton) are different in respect to their intrinsic metal content, which resulted from crustal fertilization during early orogenic and mantle plume activities. In other words, the diversity of mineral associations within the Neoproterozoic sedimentary cover could be explained by considering that the source rocks originated from different crustal blocks with distinct metalliferous fingerprints.

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João Batista G. Teixeira earned a BSc degree in Geology from the Universidade de São Paulo (1968), a MSc degree in Economic Geology from the Universidade Federal da Bahia (1984), and a PhD degree in Geosciences from the Pennsylvania State University (1994). He worked as an exploration geologist with DOCEGEO-CVRD from 1970 until 1990, in several prospecting and evaluation projects in Brazil, including Serra dos Carajás, (Pará) and the Rio Itapicuru greenstone belt (Bahia). For the moment he works as a visiting researcher with the Grupo de Metalogênese of the Universidade Federal da Bahia. His major areas of interest are mineral exploration, mineral deposits and Precambrian metallogeny.

Aroldo Misi is a Senior Lecturer at the Instituto de Geociências of the Universidade Federal da Bahia (UFBA), Brazil, and a Research Scientist of CNPq, the Brazilian Research Agency. He is the leader of the Grupo de Metalogênese of the same University and co-leader of the International Geological Correlation Programme, Project 450 (Proterozoic Sediment-Hosted Base Metal Deposits of Western Gondwana). He earned a BSc degree in Geology from the Universidade Federal da Bahia (1964) and a DEA (MSc) degree in Mineral Deposits from the Université de Paris (1967). He got a Senior Professor status in Economic Geology (LD, equivalent to PhD) from the Federal University of Bahia (1979) and did postdocs at the University of Texas at Austin (1988–1990) and at the University of Ottawa (1992). His main areas of interest are metallogeny of base-metal deposits, evolution of Neoproterozoic basins, and phosphogenesis in the Cambrian and Neoproterozoic sequences.

Maria da Glória da Silva earned a doctoral degree in Geology from Universität Freiburg im Breisgau, Freiburg, Germany in 1987. From 1983 until today she works as an Associate Professor of Economic Geology at the Instituto de Geociências, Universidade Federal da Bahia (UFBA), in Salvador, Bahia, Brazil. She is also a research member of the UFBA's Grupo de Metalogênese, with the main focus on the evolution and metallogeny of Archean-Paleoproterozoic mafic-ultramafic rocks and volcanosedimentary sequences. For the moment, Dr. Silva joins the geology team of the Brazilian Geological Survey, working as an adviser on the metallogeny issues.