The Tectonic History of the Southern Adamastor Ocean Based on a Correlation of the Kaoko and Dom Feliciano Belts

3

Miguel Angelo Stipp Basei, Hartwig Ernest Frimmel, Mario da Costa Campos Neto, Carlos Eduardo Ganade de Araujo, Neivaldo Araujo de Castro, and Claudia Regina Passarelli

Abstract

Closure of the southern Adamastor Ocean led to the development of the Neoproterozoic-Early Cambrian orogens on both margins of the present South Atlantic Ocean, which preserve a rich record of West Gondwana assembly and large-scale crustal evolution. Here we describe the distinct stages and tectonic regimes related to the evolution of the southern Adamastor Ocean as reconstructed from the geological record in southeastern Brazil, Uruguay and southwestern Africa. The welding of the Rio de la Plata/Paranapanema and African cratons was the result of a long history that generated the Dom Feliciano Belt in southeastern Brasil and Uruguay and its African counterparts, the Kaoko, Gariep and Saldania belts. Recent ideas and previous hypotheses are discussed and integrated into a tectonic model for the evolution of the southern Adamastor Ocean, largely based on comparison of the Neoproterozoic Kaoko and Dom Feliciano belts. The history of the southern Adamastor Ocean spans between 900 and 590 Ma, from the earliest records of magmatism related to Rodinia break-up (980–780 Ma), through the climax of the extensional phase that led to the opening of a vast ocean (780–640 Ma). Tectonic inversion led to subduction towards the east (in today's coordinates), which generated an extensive magmatic arc on the western margin of the Congo and Kalahari cratons (640–600 Ma) and eventually the collision between the Congo and Rio de La Plata Cratons (600–590 Ma) juxtaposing the magmatic arc and the western South American schist belts. At around 530 Ma, still under the influence of plate convergence, a positive flower structure was generated causing the extrusion of the Granite Belt, the eroded remnant of the magmatic arc, and reactivation of the doubly verging thrusts that affected the supracrustal units of the Kaoko and Dom Feliciano belts. Only at that time did deformation reach the Itajaí and Nama foreland basins.

Keywords

Kaoko and Dom Feliciano belts • Adamastor Ocean Sierra Ballena-Major Gercino suture zone • South African–South America connection

3.1 Introduction

Since the formation of the first larger masses of continental crust and preservation thereof, several cycles of continental dispersion and subsequent convergence of continental fragments have taken place. By the end of the Precambrian, four large supercontinental masses had formed (Hoffman 1991): Laurentia (North America), Gondwana (southern continents), Baltica and Siberia. In addition, several smaller peri-Gondwana blocks existed.

Comparative studies of the Western Gondwana segments in South America and Africa started with Almeida (1965), Hurley et al. (1967) and Porada (1979), and were followed by many more. In South America, recent geologic syntheses, such as those by Kröner and Cordani (2003), Cordani et al. (2010) and Brito Neves and Fuck (2013), divided the Precambrian rocks into two major geotectonic domains, roughly bounded by the Transbrasiliano Lineament: the Amazonas or pre-Brasiliano domain (of Laurentian affinity) and the Brasiliano domain (of Gondwana affinity). The latter

M. A. S. Basei (✉) · M. da C. Campos Neto · C. R. Passarelli
Geosciences Institute, University of São Paulo, São Paulo, Brazil
e-mail: baseimas@usp.br

H. E. Frimmel
Institute of Geography and Geology, University of Würzburg, Würzburg, Germany

H. E. Frimmel
Department of Geological Sciences, University of Cape Town, Rondebosch, South Africa

C. E. G. de Araujo
Geological Survey of Brazil, Rio de Janeiro, Brazil

N. A. de Castro
Geosciences Institute, Federal University of Santa Catarina, Florianópolis, Brazil

S. Siegesmund et al. (eds.), *Geology of Southwest Gondwana*, Regional Geology Reviews,
https://doi.org/10.1007/978-3-319-68920-3_3

comprises a Neoproterozoic framework of orogens adjacent to cratonic entities, such as the Rio de la Plata, Paranapanema and São Francisco cratons (Alkmim and Teixeira 2017; Assumpção et al. 2017; Barbosa and Barbosa 2017; Teixeira et al. 2017).

The geological records of convergent oceanic plate regimes and a succession of collisions between continental blocks along a continuous belt define the Western Gondwana Orogenic System (Ganade Araujo et al. 2012, 2016). This orogenic system reflects the diachronous closure of a large ocean—the Ocean (Caby 2003; Cordani et al. 2013; D'Agrela-Filho and Cordani 2017)—along a suture that is represented by today's Transbrasiliano Lineament, a product of a long-term geological history of *c.* 250 million years. As the example of the Mozambique Orogen in Eastern Africa-Antarctica (Squire et al. 2006), the Western Gondwana Orogenic System, as a result of its deep continental deformation, most likely formed a huge mountain chain by the end of the Neoproterozoic, comparable with today's Alpine-Himalayan system of orogenic belts (Ganade Araujo et al. 2014).

The paleogeographic starting point for the Neoproterozoic tectonic history, including the opening and closure of the Farusian-Goiás Ocean, remains a matter of debate but is generally assumed to start with the existence of a supercontinent—that is, Rodinia. Various configurations have been proposed for Rodinia, such as Urung (1997), and more recently Fuck et al. (2008) and Li et al. (2008). Alternative paleogeographic reconstructions of the Rodinia supercontinent, with continental masses of Laurentian and Gondwana affinities, such as the Rio de la Plata Craton, have been suggested on geological (Cordani et al. 2003a, b; Kröner and Cordani 2003; Johnson et al. 2005; Teixeira et al. 2013; Fuck et al. 2017) and geophysical grounds (Pisarevsky et al. 2003; Tohver et al. 2006; D'Agrela-Filho and Cordani 2017). An alternative model involves a large ocean between Rodinia and proto-Gondwana (Tohver et al. 2006), next to the Amazonian-Rio Apa Block and between Pampia (Ramos et al. 2010) and Rio de la Plata—named Clymene Ocean, as proposed by Tohver et al. (2010). The corresponding rock record is suggested to be in the Paraguai-Araguaia belts and the Pampean magmatic arc.

A map of Western Gondwana (Fig. 3.1) shows the orogenic systems related to the diachronous closure of the Farusian-Goiás and Adamastor oceans, and the continental blocks and cratons involved in plate convergence in the Neoproterozoic. While oceanic plate convergence in the South American sector marked the Farusian-Goiás domain in the Tonian to early Cryogenian periods (Cordani et al. 2013), divergent plate regimes segmented the Congo-São Francisco (Tack et al. 2001; Pedrosa-Soares et al. 2008; Babinski et al. 2012; Affaton et al. 2016) and Kalahari-Rio de la Plata continental blocks (Basei et al. 2005, 2008a, 2011a; Frimmel et al. 2011, 2013), resulting in the opening of the Adamastor Ocean. In this context, the Luís Alves and Curitiba continental blocks would represent microcontinents with an active margin by the end of the Neoproterozoic (Basei et al. 1992, 1998, 2000, 2009).

Beyond the Mesoproterozoic units of the Irumide Belt (Johnson et al. 2005, 2007; De Waele et al. 2009; Fernandez-Alonso et al. 2012; Hauzenberger et al. 2014), between the Congo and Kalahari cratons, the Damara Belt reflects the evolution from continental rifting to spreading and formation of a narrow oceanic basin in the Ediacaran (Miller et al. 2009; Frimmel et al. 2011; Lehmann et al. 2015; Nascimento et al. 2016). This suggests an aulacogen opening of lithospheric proportions, synchronous with the closure of the Adamastor Ocean.

The Ediacaran formation of magmatic arcs in active continental margins (Campos Neto and Figueiredo 1995; Basei et al. 2000, 2008a; Prazeres Filho et al. 2003; Leite et al. 2007; Frimmel et al. 2013; Hueck et al. 2016; Philipp et al. 2016a, b; Tedeschi et al. 2016; Heilbron et al. 2017) marked the end of ocean opening. Except for the hot roots of the Araçuaí Orogen (Valeriano et al. 2016), plate tectonic processes were fast and culminated in end-Ediacaran collisions (Basei et al. 2008a, 2010; Faleiros et al. 2011; Santos et al. 2015), which were followed by lithospheric extensional regimes, with subalkaline volcanism and continental basins (Teixeira et al. 2004b), and with elongated orogen-parallel provinces of A-type alkaline plutonism (Vlach and Galda 2007; Janasi et al. 2009; Pimentel 2016).

The term 'Adamastor Ocean' was originally coined by Hartnady et al. (1985) based on the areal distribution of mafic oceanic crustal rock assemblages in southwestern Africa, notably the Matchless amphibolite zone in the southern Damara Belt and the metavolcanic rocks of ophiolitic affinity in the Gariep Belt. These oceanic crustal rock suites continue south(west)ward from the Kalahari Craton towards southern South America and the Transantarctic Province. Oceanic opening towards the north up to the São Francisco-Congo gulf, ancestor of the Araçuaí-West Congo Orogen (Pedrosa Soares et al. 2001; Degler et al. 2017), seems to have been linked with the peripheral collision of the São Francisco Craton against the Paranapanema Block and Amazonian Craton. The Ediacaran magmatic arcs mark the end of ocean opening and record an extensive system of accretionary orogens that led to the Ediacaran-Cambrian assembly of western Gondwana.

The term 'Adamastor Ocean' is here considered in a broader sense than originally proposed by Hartnady et al. (1985), who regarded it as a kind of proto-South Atlantic ocean. In the current view, illustrated in Fig. 3.1, this Neoproterozoic ocean would include several branches, such as those that eventually led to the Ribeira and Araçuaí belts. In their midst several continental fragments with different shapes and sizes existed—namely the Nico Peres,

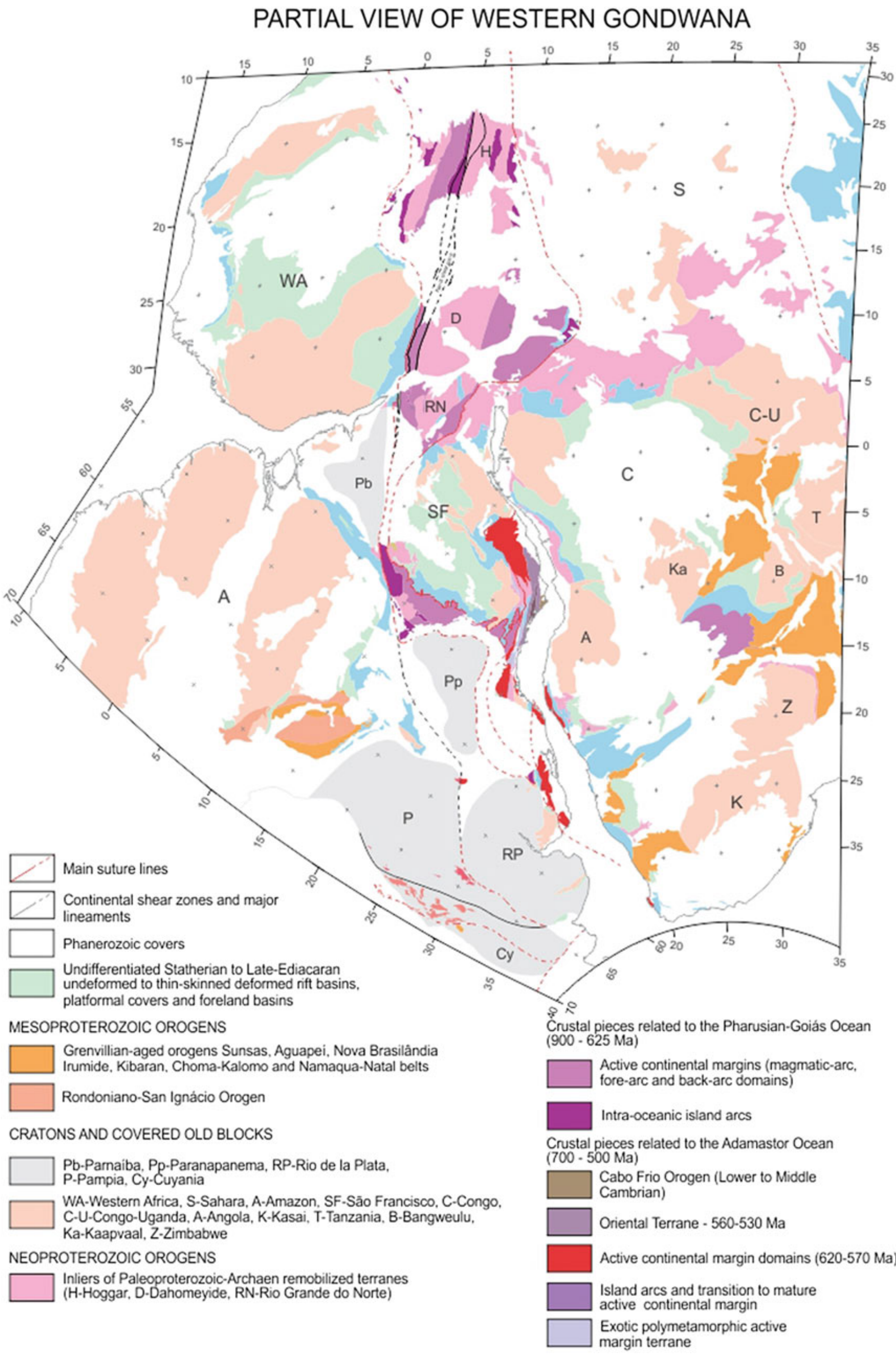

Fig. 3.1 Western Gondwana reconstruction (modified from de Wit et al. 1988). *RP* Rio de la Plata Craton; *P* Pampia Block; *A* Amazonian Craton; *SF* São Francisco Craton; *Pp* Paranapanema Block; *WA* West Africa Craton; *Pb* Parnaíba Block; *C* Congo Craton; *C–U* Congo-Uganda Craton; *A* Angola Craton; *KA* Kazai Block; *B* Bangweulu Block; *T* Tanzania Craton; *Z* Zimbabwe Craton; *K* Kalahari Craton; *Cy* Cuyania Terrane; *H* Hoggar Inlier; *D* Dahomei Inlier; *RN* Rio Grande do Norte Inlier

Encantadas, Luis Alves, and Curitica blocks—and in Africa possibly the Angola cratonic block. All these segments were diachronously amalgamated around 600 Ma during the closure of the Adamastor Ocean.

3.2 Pan-African/Brasiliano Belts Along the Southern South Atlantic Margins

Remnants of former southwestern Gondwana exist on both sides of the present South Atlantic Ocean with Neoproterozoic fold belts along the coasts and old cratons towards the interior. This symmetry is defined by a central granitic belt bounded on both sides by fold-and-thrust belts with opposite tectonic vergence: towards the west in the Dom Feliciano Belt and to the east in the Kaoko and Gariep belts (Trompette 1997; Goscombe and Gray 2007; Basei et al. 2008a). Supracrustal rocks predominate on the African side, where only small magmatic segments may correspond to the magmatic arc associated with the tectonic evolution of the Neoproterozoic belts. The domain on the African side that most closely resembles a magmatic arc occurs in the westernmost Kaoko Belt in the form of the Skeleton Coast granitoids. This African segment most likely corresponds to the 1200 km-long Granite Belt in the Dom Feliciano Belt in southeastern South America. As the main goal of this chapter is to characterize the geological history of the Southern Adamastor Ocean, we shall focus on a comparison between the Kaoko and Dom Feliciano belts.

3.2.1 Dom Feliciano Belt

The Dom Feliciano Belt (DFB) represents the geotectonic unit of greatest continuity of the southern portion of the Mantiqueira Province (Almeida et al. 1981) (Fig. 3.2). It defines an extensive north-northeast-trending polyphase belt of some 1200 km length, which occupies the whole southeastern portion of Brazil and Uruguay (Fragoso Cesar, 1980; Basei et al. 2000, 2008a, 2010; Oyhantçabal et al. 2009b; Philipp et al. 2016a, b). From its northern limit in Santa Catarina to its termination in Uruguay, it unifies three crustal segments with distinct lithological and tectonic characteristics. These are, from southeast to northwest, the Granitoid Belt (deformed calc-alkaline to alkaline granitoid rocks), a metamorphic (greenschist to amphibolite facies) volcano sedimentary belt, and a former foreland basin filled with anchimetamorphic sedimentary and volcanic rocks. In spite of younger sedimentary cover in many places, the continuity of these three segments is indicated by similarities in rock types, structural characteristics and gravimetric signatures (Schukowsky et al. 1991; Halinann and Mantovani 1993). The present constitution of the DFB was reached only in the Ediacaran Period when its different components were juxtaposed.

Northeast-southwest contacts between the different domains and the tectonic vergence pointing to the foreland westwards are conspicuous features of the entire DFB. This late geometry reflects different pulses of an overall continuous tectonic process between 640 and 530 Ma (Basei et al. 2008a).

The Dom Feliciano schist belt, referred to in the following as the Schist Belt, constitutes the Brusque (Santa Catarina), Porongos (Rio Grande do Sul) and Lavalleja (Uruguay) supracrustal sucessions, which represent the passive margin deposit on the western side of the Adamastor Ocean. Continuity of these supracrustal belts, besides geophysical evidence, is suggested by several similarities, including the predominance of lower-pressure metamorphism, the same geotectonic position of all sequences and also granitic magmatism intrusive into these supracrustal rocks. These units are polydeformed sequences, with three folding phases associated with a northwestward mass transport, which evolved to late lateral transpression. In structural terms the main foliation in the majority of the metamorphic rocks is a syn-peak metamorphic S_2 foliation. The regional metamorphism is of greenschist facies, locally reaching the lower amphibolite facies (Silva et al. 1980; Sanchez-Bettucci et al. 2001, 2004; Philipp et al. 2004; Basei et al. 2011b).

Along the Schist Belt, syn- to late-collisional, *c.* 600 Ma granitoids were emplaced into the supracrustal rocks and developed contact metamorphic aureoles that post-date the main foliation of the regional metamorphic rocks. They are more frequent in the Brusque Belt and decrease in abundance towards the south, with hardly any expression in the rocks of the Lavalleja Group in Uruguay (Plate 3.1).

Despite numerous new U–Pb detrital zircon age data, the precise age of sedimentation along the entire belt remains poorly constrained. The basement of all sedimentary units is Paleoproterozoic (Basei et al. 2008a, 2013). Late Neoproterozoic granite emplacement at around 600 Ma sets a minimum limit for the age of sedimentation. Volcanic rocks interspersed in the sedimentary sequences indicate ages along the belt that vary between 780 and 640 Ma.

3.2.2 Kaoko Belt

In southwestern Africa, the Pan-African Orogeny led to a system of three coast-parallel belts—namely, the Kaoko, Gariep and (western) Saldania belts—and an intracontinental belt, the Damara Belt (Fig. 3.3). This system evolved through successive phases of rifting and continental break-up, drifting, subduction and continental collision. In this chapter the emphasis is placed on the Kaoko Belt.

A range of basement rocks are exposed in the Kaoko Belt, most prominently in the Kamanjab Inlier and the Epupa Complex, containing Archean orthogneiss of *c.* 2600 Ma

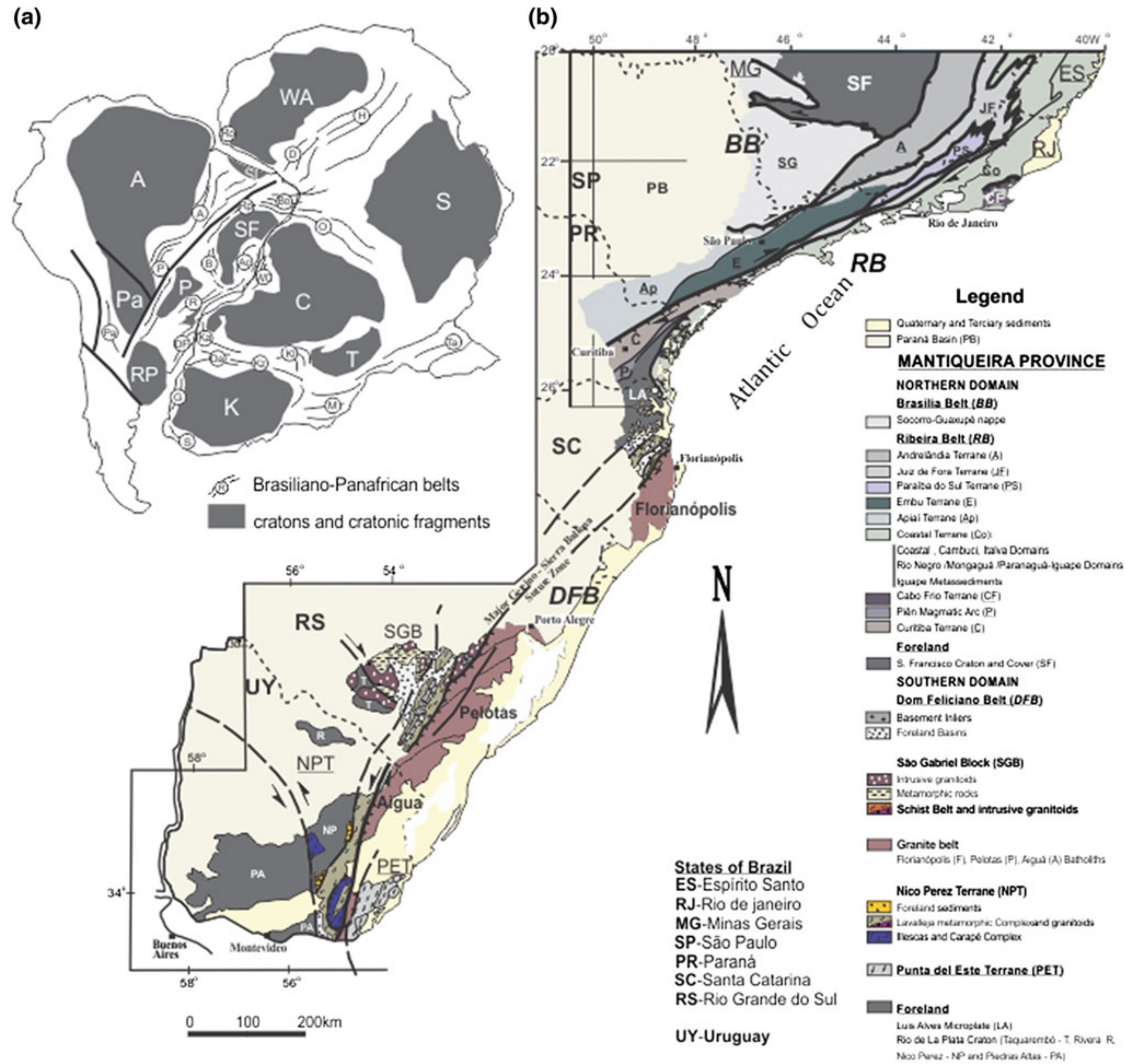

Fig. 3.2 Main geological features of Southern Mantiqueira Province focusing on the Dom Feliciano Belt (Brazil–Uruguay) **a** Reconstruction of West Gondwana after Heilbron and Machado (2003) and Heilbron et al. (2017); de Wit et al. (1988) and Cordani et al. (2013), showing cratonic blocks and Brasiliano–Panafrican belts. Cratons shown in grey: *A* Amazonia; *C* Congo; *K* Kalahari; *LA* Luis Alves; *P* Paranapanema; *SF* São Francisco; *WA* West Africa. Brasiliano–Panafrican belts (ringed): *Bo* Borborema; *Rp* Rio Preto; *A* Araguaia; *Aç* Araçuaí; *P* Paraguai; *B* Brasília; *R* Ribeira; *DF* Dom Feliciano; *Pa* Pampean; *H* Hoggar; *D* Dahomey; *Ro* Rockelides; *O* Oubangides; *Ta* Tanzania; *WC* West Congo; *Ka* Kaoko; *Da* Damara; *K/Z* Katangan/Zambezi; *Kl* Katanga-Lufilian Arc; *M* Mozambique; *G* Gariep; *S* Saldania. Location of the Mantiqueira Province is shown. **b** General outline of the Mantiqueira Province (Brazil–Uruguay). Simplified from Basei et al. (2008a), Passarelli et al. (2011, unpublished)

(Seth et al. 1998). Mesoproterozoic rocks occur in several places, predominantly quartzite and amphibolite with subordinate felsic rocks, with ages grouping in the 1350–1500 Ma interval (Seth et al. 1998; Kröner et al. 2004; Goscombe et al. 2005).

The Kaoko Belt has been subdivided into several zones. The Eastern Kaoko Zone consists of Neoproterozoic platform sediments on the western margin of Congo Craton. The metamorphic grade is only very low. A marine ingression prior to 750 Ma is evident from a carbonate, deep-water rhythmic argillite and shallow-water stromatolite succession (Ombombo Subgroup), which lies on siliciclastic deposits of the Nosib Group and is covered by the Chuos Formation diamictite (Hoffman et al. 1998).

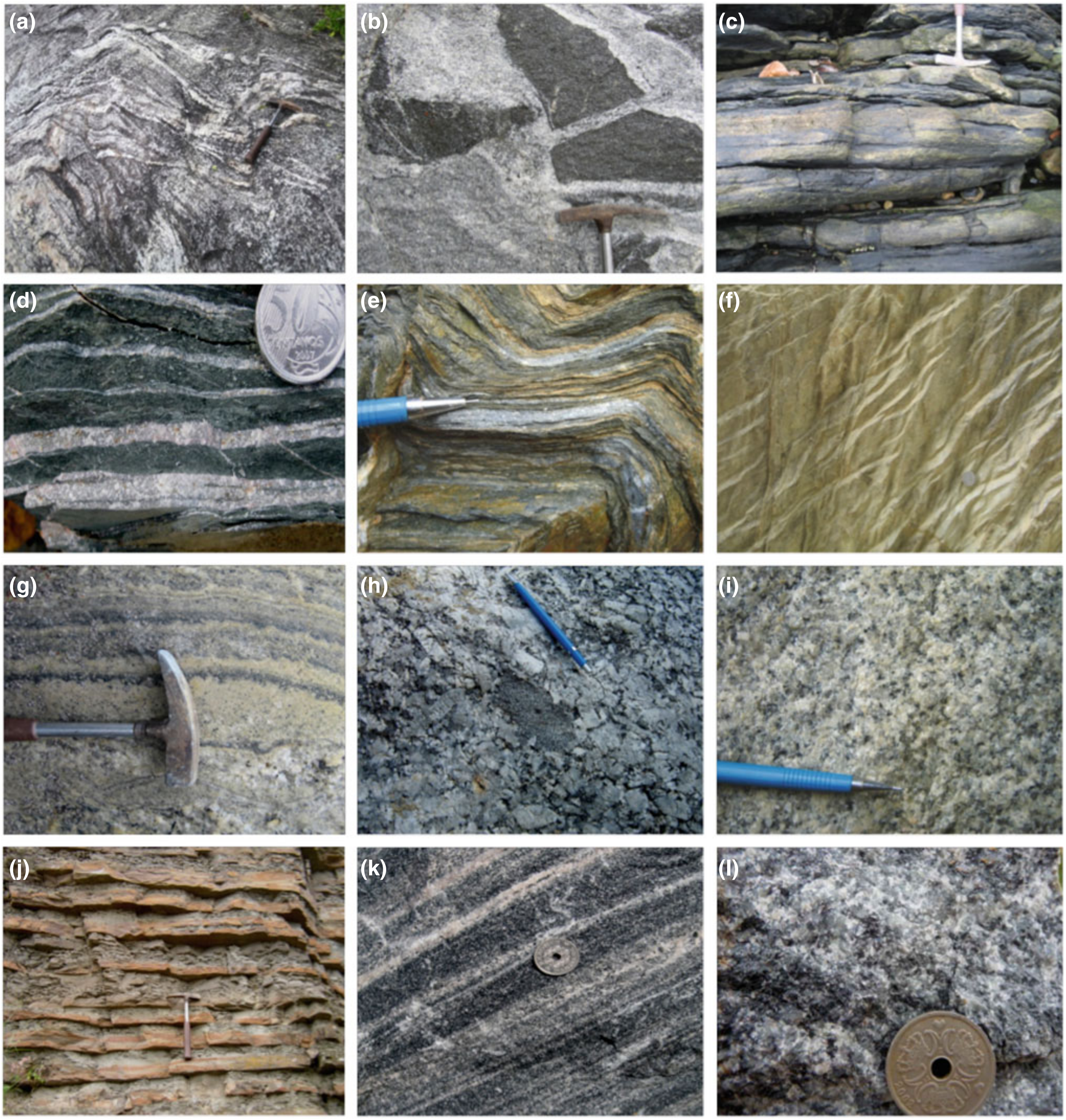

Plate 3.1 Field photographs from the Dom Feliciano Belt. Granite Belt: **a** banded gneisses of Aguas Mornas Complex; **b** São Pedro de Alcantara biotite-monzogranite with mafic enclaves; Schist Belt: **c** 640 Ma amphibolite interlayered with metasedimentary units; **d** thinly bedded limestone; **e** late-stage folds in biotite-quartzschist; **f** two sets of crenulation folds deforming quartz-sericiteschist; Granitoids intrusive into the Schist Belt: **g** São João Batista banded tourmaline-muscovite leucogranite; **h** coarse-grained Valsungana biotite granite with microgranular enclaves; **i** homogeneous Nova Trento two mica granite; Foreland Basin: **j** banded turbidite of Itajaí Basin; Luis Alves Craton (Foreland): **k** orthopyroxene banded gneiss; **l** typical massif charno-enderbitic gneiss

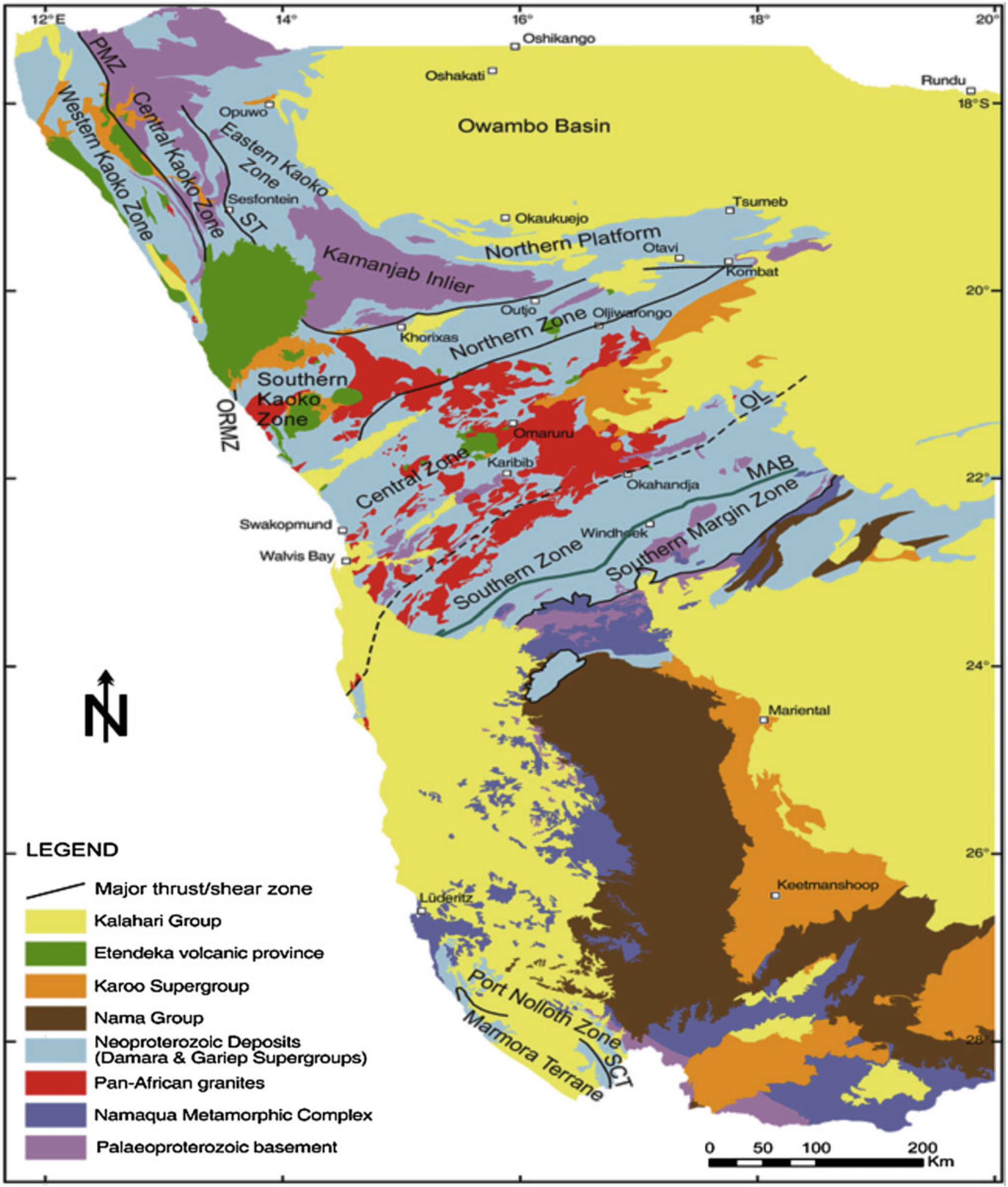

Fig. 3.3 Main tectonostratigraphic units of southwestern Africa. Lineaments: *ORMZ* Ogden mylonitic zone; *PMZ* Purros mylonitic zone; *ST* Sesfontein thrust; *SCT* Schakalsberge thrust. After Frimmel et al. (2011)

The Central Kaoko Zone is bounded to the east by a shallow late Pan-African thrust zone (Sesfontein Thrust) (Goscombe et al. 2003), and to the west by the mylonitic Purros Shear Zone (Fig. 3.3). It is composed of an Archean to Paleoproterozoic gneissic-granitic basement, with Paleo- to Mesoproterozoic granitoid bodies, and covered by Neoproterozoic metapelitic to metapsammitic supracrustal rocks (Seth et al. 1998; Kröner et al. 2004). Konopásek et al. (2008) reported U–Pb zircon ages (SIMS) between 840 and 805 Ma for felsic rocks of bimodal metavolcanic suites and interpreted them as dating continental rift-related volcanism. The metamorphic grade increases from east to west, passing from lower greenschist to upper amphibolite facies, and reflecting a Barrovian-type P/T gradient.

Both basement and sedimentary cover display an intense sinistral transpressional superposed fabric and folds associated with series of thrusts and nappes transported eastwards (Goscombe et al. 2003; Will et al. 2004). The sequences observed in the Ugab zone correspond to turbidites (Gray et al. 2006) containing two thin cap carbonate units possibly associated with Sturtian glaciation at 720–700 Ma (oldest) and the youngest with the Ghaub Formation diamictite of supposedly Marinoan age of 635 Ma (Hoffman et al. 1998; Hoffmann et al. 2004).

The Western Zone of the Kaoko Belt, also referred to as Coastal Terrane (Fig. 3.3), records two high-grade (upper amphibolite to granulite facies) low-P/high-T metamorphic episodes around 645 and 550 Ma (Franz et al. 1999) associated with Neoproterozoic granitoids. Type-I calc-alkaline granitoids of 650–630 Ma age are also present (Seth et al. 1998; Konopásek et al. 2016). All rocks in this domain were affected by sinistral shearing, isoclinal folding (Goscombe et al. 2003) and high-grade metamorphism (Seth et al. 1998; Franz et al. 1999; Konopásek et al. 2008). The Three Palms Mylonite Zone defines the eastern limit of the Coastal Terrane. It represents, analogous to the Major Gercino-Sierra Ballena Shear Zone on the western flank of the Granite Belt in the DFB, a low-angle shear zone that in the course of progressing crustal shortening was gradually transformed into high-angle faults with a predominantly directional component.

The abundance of calc-alkaline intrusive rocks, which form a large batholith (the Skeleton Coast Batholith), is generally explained as representing a former magmatic arc in the Coastal Terrane. These rocks range in composition from mafic, intermediate to felsic (Seth et al. 1998; Franz et al. 1999; Masberg et al. 2005), and were emplaced into metamorphosed supracrustals rocks (Goscombe and Gray 2007). The absence of a tectonic boundary between the metasedimentary cover and the rocks of the Skeleton Coast Batholith suggests an intimate relation between deposition of the metasedimentary rocks and the evolution of the magmatic arc. Interestingly, similar sedimentary cover as in the Coastal Terrane and with the same detrital zircon populations also occurs as roof pendants of the granitoids in the DFB (Basei et al. 2008a). Part of the detrital zircon age patterns of the metasedimentary units in the Coastal Terrane cannot be reconciled with any source in the Central Zone of the belt but match very well the age pattern of the magmatic arc rocks (Goscombe and Gray 2007, 2008; Konapásek et al. 2014; Basei et al. unpublished data). It is therefore concluded that the Coastal Terrane as a whole (magmatic arc and its sedimentary cover) would be a para-autochthonous unit and not an exotic terrane without genetic links with the rest of Kaoko Belt.

In a similar way to that observed in the DFB, where a set of S-type granitoids occurs adjacent to the Major Gercino-Sierra Ballena Suture Zone, marking the contact between the Schist Belt and the magmatic arc, a significant volume of S-type granitoids also marks the eastern contact of the magmatic arc of the Coastal Terrane in the vicinity of the Three Palms Mylonite Zone (Goscombe and Gray 2007; Konapásek et al. 2008, 2014) (Plate 3.2).

3.3 Depositional Age and Provenance Constraints from Detrital Zircon Ages from the Dom Feliciano and Kaoko Belts

U–Pb ages (SHRIMP and LAICPMS) on detrital zircon have been used as the main tool to define the provenance and maximum age of deposition of the metasedimentary rocks that constitute the schist belts. When this type of information is combined with ages of volcanic rocks interlayered in sedimentary sequences as well as ages of metamorphic and magmatic events, it becomes possible to reconstruct the geological evolution of a given belt with a high degree of confidence.

Zircon age dating on mylonitic quartzite that occurs in the northern portion of the Brusque Group (Hartmann et al. 2003) yielded largely Paleoproterozoic values in the range 2180–2090 Ma and a single crystal with 2220 Ma. Basei et al. (2008a) analysed two samples of metasedimentary rocks, a volcanosedimentary micaschist and a garnet-biotite schist. The zircon grains therein revealed age peaks in the ranges 2250–1700, 1500–1300 and 1300–1100 Ma, and two grains with anomalously young ages of 540 and 570 Ma. A metaconglomerate at the top of the metavolcancosedimentary unit in Morro do Carneiro gave detrital zircon ages mainly between 2100 and 1850 Ma with some older, Archean grains (2600–3000 Ma). In this sample the main age peak is around 2000 Ma and the youngest concordant age is 1250 Ma. Another sample, from a quartzitic bed in the micaschist, yielded a similar age distribution, with populations of 1500–1300 and 2200–1800, and some Archean values between 2600 and 3100 Ma. The main peak is at 2200 Ma (Yamamoto and Basei 2009).

Plate 3.2 Field photographs from the Kaoko Belt. Basement rocks: **a** deformed granitoid of Kamanjab Inlier; **b** sheared pink megacrystic granite at Marien Fluss, Kunene River; Eastern Domain (carbonate platform); **c** thinly bedded limestone of the Tsumeb formation; **d** limestone of the Hüttenberg formation; Central Domain; **e** general view of medium-grade Kaoko mica schist just above the Sesfontein thrust; **f** folded diamictite of Chuos formation; Orogen core; **g** deformed coarse-grained biotite granite, near Purros shear zone; **h** Porphyroclastic augen gneiss of three palm Mylonite zone; Costal Terrane; **i** banded high-grade migmatite with metasedimentary paleosome; **j** feldspathic garnet-mica schist of supracrustal units near Terrace Bay; **k** deformed tonalite with elongated mafic enclaves; **l** deformed biotite monzogranite with elongated mafic bands

Considering the detrital zircon age patterns of the Brusque Group, the predominance of Paleoproterozoic values is evident, as well as a moderate Archean contribution. In terms of provenance, the origin of these zircon grains can be essentially South American, with the Archean to Paleoproterozoic domains constituting the Luis Alves, Paranapanema and Rio de la Plata cratons, as well as the Camboriú Complex, representing the likely source areas. On the other hand, the origin of the few Mesoproterozoic ages found in these rocks, with values between 1200 and 1300 Ma, is more problematic as there are no known rocks of this age exposed in southern and southeastern Brazil. A probable African origin for these Mesoproterozoic zircons has been suggested by Basei et al. (2005, 2008a). The two young grains obtained, with ages of 540 and 570 Ma, confirm the Neoproterozoic depositional age of the Brusque Group. However, the values are much younger than one might expect and may reflect loss of radiogenic Pb.

Late Cryogenian deposition of most of the Brusque Group is confirmed by age data of around 637 and 640 Ma obtained on intercalated felsic and mafic metavolcanic rocks (Silva et al. 2002; Basei et al. 2011b). In addition, U–Pb zircon ages from four calsilicatic samples with a probable tuffecous contribution indicate several detrital zircon populations, with age peaks in the ranges 2350–2040, 2000–1880 and 1270–780 Ma, whereas the age of volcanism is around 640 Ma (Brentan 2011).

Recent U–Pb detrital zircon studies on the Porongos Group revealed the existence of two sedimentary sucessions with different ages and tectonic contexts. An older sedimentary sequence is Tonian to Cryogenian, as evidenced by 810 and 770 Ma felsic and mafic metavolcanic rocks (Porcher et al. 1999; Chemale 2000; Gruber et al. 2011; Saalmann et al. 2011; Arena et al. 2017; Pertille et al. 2017). In the enclosing sedimentary rocks, a younger population of detrital zircon with ages between 800 and 1300 Ma is distinguished from an older group with ages mainly between 2000 and 2200 Ma and a few Archean values (Gruber et al. 2011; Höfig et al. accepted). The younger depositional sequence is Ediacaran, with 610 Ma metatuff layers (Höfig et al. accepted) intercalated in the psamopelitic sedimentary rocks, and deformed 600 Ma alkaline leucosyenogranite (Zvirtes et al. 2015) crosscutting the metasedimentary rocks. The detrital zircon age pattern of the Ediacaran succession is marked by 580 and 610 Ma major peaks, with subordinate populations between 2200 and 2000 Ma and some Archean values between 2900 and 2700 Ma (Pertille et al. 2015b, 2017; Höfig et al. accepted).

The possibility of Paleo- to Mesoproterozoic metasedimentary units having formed part of the basement of the Porongos Basin is suggested by the existence of quartzite beds that contain detrital zircon populations of quite different provenance. These rocks occur on the western edge of the Santana Dome, the best exposure of the Paleoproterozoic basement of the Porongos Group occurs. Detrital zircon in this quartzite yielded ages in the 3200–1990 Ma range with a main peak around 2100 Ma (Hartmann et al. 2004; Gruber et al. 2011; Pertille et al. 2015a). A few grains yielded an age of *c*. 1750 Ma (Gruber et al. 2011) but no Meso- or Neoproterozoic data has been obtained.

The absence of Neoproterozoic detrital zircon grains is a critical feature that continues into the mica schists of the eastern and southern flanks of the Santana Dome. There, however, Mesoproterozoic detrital zircon ages from 1010 to 1060 Ma are abundant. In addition, the sedimentary succession contains intercalations of acidic and intermediate volcanic rocks that have been dated around 770 Ma (Porcher et al. 1999; Gruber et al. 2011; Saalmann et al. 2011; Pertille et al. 2017), thus suggesting a correlation with the oldest Tonian succession of the Porongos Group.

The oldest Tonian-Cryogenian metasedimentary succession of the Porongos Group corresponds to remnants of a marginal basin fill (including the rift units) that were laid down on the margin of the Rio de la Plata and Paranapanema cratons at the western end of the Adamastor Ocean. The Ediacaran upper units of the Porongos Group are related to the synorogenic deposits of the collisional phase of the DFB. The Meso-Paleoproterozoic quartzites may correspond, similar to those observed in the Kaoko Belt, to an old platform cover.

From the Lavalleja Group, which represents the continuation of the Schist Belt in Uruguay, only few data is available. SHRIMP U-Pb detrital zircon ages for two samples were presented by Basei et al. (2008a). The first corresponds to a quartz-sericite schist of the Fuente del Puma Formation (Sanchez-Bettucci et al. 2001, 2004) collected from a well-exposed outcrop on Road 60. A range of zircon ages was obtained with Archean (2600–3400 Ma), Paleoproterozoic (1780–2400 Ma) and Neoproterozoic ages (600–1000 Ma). The age pattern observed in a sample from the Zanja del Tigre Formation (Sanchez-Bettucci et al. 2001, 2004) is quite different from the previous sample. This rock corresponds to a rhythmic metapsammitic rock collected on Road 12. In this sample, some Archean grains were found (some older than 3000 Ma), with the majority being Paleoproterozoic (1800–2300 Ma). No Meso- or Neoproterozoic zircon grains were found in this sample. Here the older zircon populations are of particular interest because no corresponding Archean units are known so far in Uruguay.

On the African side, the number of provenance studies on (meta)sedimenatary units of the Kaoko Belt remains limited. Nevertheless, the control on the timing of sediment deposition is reasonably good thanks to age data for interlayered volcanic rocks. An additional control is provided by the age of metamorphism and granitoids that cut these metasedimentary units.

Two of the three lithostructural segments that make up the Kaoko Belt were studied by Konapásek et al. (2014), who presented a set of detrital zircon U–Pb ages. For the Central Domain, three samples yielded a large variation of ages, with main peaks at 650–750, 1250–1400 and 1850–2000 Ma. Only a few grains gave Archean ages of 2600–2700 Ma. The Orogen Core, located between the Purros and Three Palms Mylonite shear zones, contains detrital zircon grains with the main age groups around 650, 1000, 1450 and 1800 Ma. Neoproterozoic ages in this segment are more abundant than in the Central Domain. The well-documented increase in the grade of metamorphism towards the Orogen Core is well reflected by an abundance of U–Pb zircon overgrowth ages between 570 and 620 Ma. In the Coastal Terrane, the vast majority of detrital zircon grains in the metasedimentary rocks is Neoproterozoic in age, with a main peak around 650 Ma. Minor age peaks are at 950–1050, 1250–1050, 1850 and 2150 Ma. High-grade metamorphism in the Coastal Terrane is recorded in orthogranulitic gneisses and reflected by metamorphic zircon overgrowths with ages of 630–650 Ma.

For the metasedimentary units that occur south of the Kamanjab basement inlier, a set of U–Pb results in detrital zircon were presented for the Otavi-Swakop groups ranging from Nabis Formation to the Mulden Group molasse (Nascimento et al. 2017). The age pattern observed by Nascimento et al. shows an unimodal distribution around 1750 Ma for the Nabis Formation whereas in the Chuos Formation of the Nosib Group, additional populations with ages of *c*. 1250 Ma and to a lesser extent 740 Ma exist. The latter is in good agreement with the intercalated volcanic rocks that provided ages between 745 and 760 Ma (Hoffman et al. 1996; DeKock et al. 2000; Halverson et al. 2002; Nascimento et al. 2016) for spatially associated diamictite, which has been related to the Sturtian glaciation. In the Ghaub/Black River Formation, detrital zircon ages of around 1970 Ma predominate with a few grains having older ages of 1000–2600 Ma. In addition, younger values of 660–680 Ma are in agreement with a Marinoan age generally postulated for these units based on a precise U–Pb zircon age of 635 Ma obtained on an intercalated tuff layer in a supposedly correlatable unit further south in the Damara Belt (Hoffman et al. 2004). In contrast to the above, the molasse sediments of the Mulden Group contain detrital zircon grains that are predominantly Neoproterozoic (650–710 Ma), with a second population around 1030 Ma and minor contributions from Paleoproterozoic ($\sim$1860 Ma) and Archean (2600 Ma) sources.

For the intracontinental branch of the Damara Belt, Foster et al. (2015) could distinguish sediment sources in the Congo Craton and in the Kalahari Craton. The former is characterized by age peaks of 1150–1000 and 800–600 Ma, whereas the latter is characterized by ages between 1300 and 1150 Ma. This difference led them to conclude that both cratons were widely separated from each other at the end of the Mesoproterozoic and became juxtaposed only in Ediacaran times. Such a strict separation of Congo and Kalahari provenance is, however, problematic because elsewhere the Kalahari Craton contains voluminous units with ages that correspond to those allegedly typical of the Congo Craton—for example, in the Bushmanland Subprovince of the Namaqua-Natal Belt (Robb et al. 1999) and in the Richtersveld Igneous Complex (Frimmel et al. 2001).

Foster et al. (2015) also suggested a maximum depositional age for the Mulden Group in the Northern Foreland of $\sim$590 Ma, which is supported by the youngest concordant detrital zircon ages of *c*. 620 Ma obtained from the Hartmann Subgroup (Goscombe et al. 2005).

The main sediment sources in both the DFB and the Kaoko Belts are evidently their basement and adjacent cratons (Goscombe et al. 2005; Basei et al. 2008a; Konapásek et al. 2014; Foster et al. 2015; Pertille et al. 2015a, 2017; Höfig et al. accepted; Nascimento et al. 2017). In most sedimentary sequences of these two belts, zircon populations with Paleoproterozoic ages predominate. Mesoproterozoic ages are abundant on the African side but are very minor on the South American side of the DFB, with only few such grains in the Brusque Group and increasing in number towards the south. However, in both belts, Cryogenian and Ediacaran zircon populations predominate in the younger syn- to late-orogenic units. This is due to the extrusion of the magmatic arc, represented by the Granite Belt, which became a high ground and thus constituted the main sediment source for the younger units in both belts. Similarly, the Coastal Terrane metasedimentary units are unequivocally related to magmatic arc evolution and probably had the Granite Belt as their main sediment source area. Metasedimentary remnants that occur as large roof-pendants in the middle of the Granite Belt probably have an African provenance of Meso- to Neoproterozoic age, which seems to be a fingerprint of Neoproterozoic supracrustal rocks of (southern) African affinity.

3.4 Tectonic Model

In the last 15 years, advances in the correlation of tectonothermal events, and Neoproterozoic sedimentation history on both sides of the Southern Atlantic Ocean have helped to fill gaps in the tectonopaleogeographic interpretation of the Neoproterozoic fold belts in southwestern Africa and southeastern South America.

A new tectonic model is proposed here, which hinges essentially on five findings: (1) The westernmost domain of the Kaoko Belt (Coastal Terrane) can be correlated with the Florianópolis-Pelotas-Aiguá magmatic arc in the DFB;

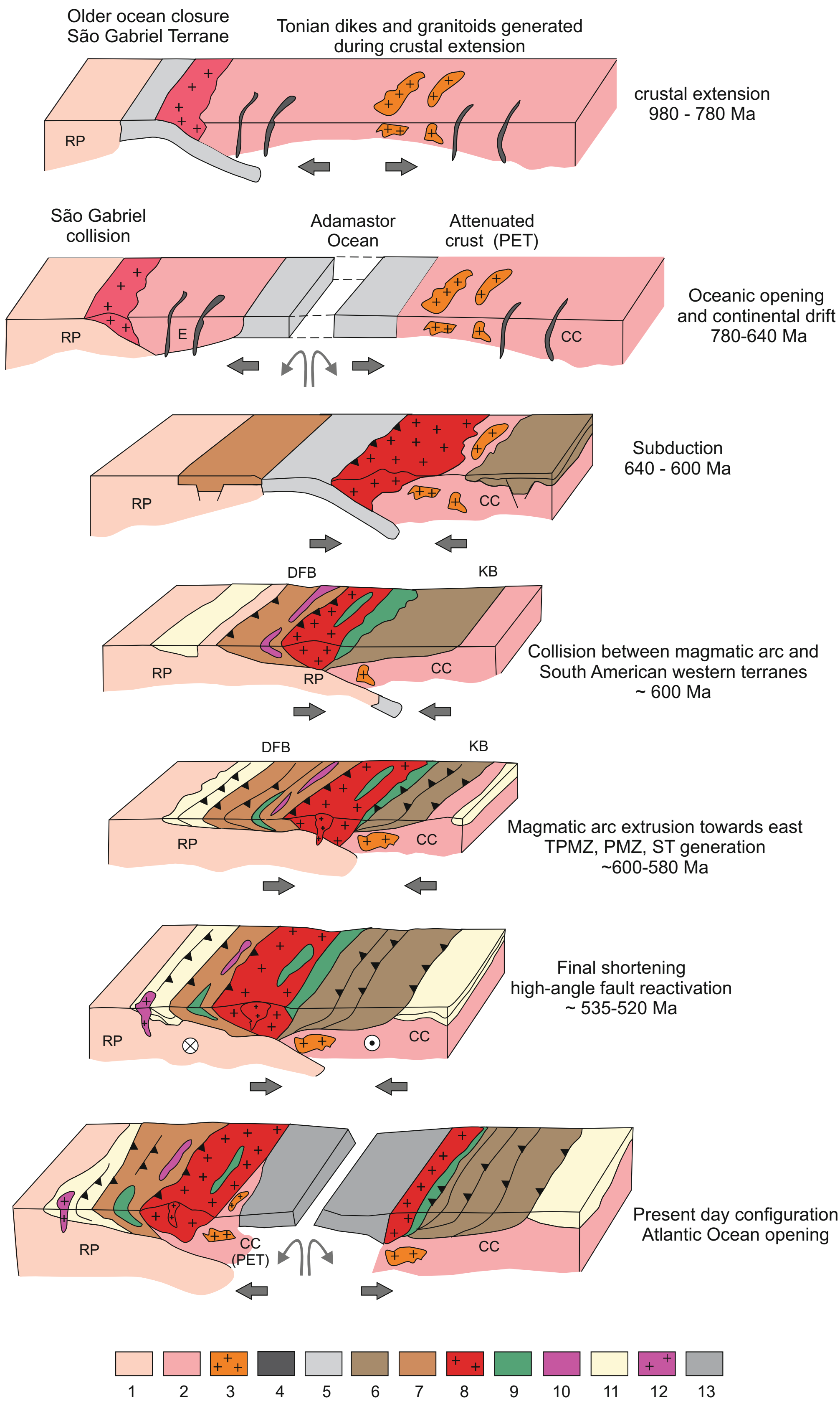

Fig. 3.4 Principle tectonic stages in the evolution of the Adamastor Ocean from Rodinia's fragmentation around 850 Ma to Adamastor closure *c*. 600 Ma: 1—Rio de la Plata Craton; 2—Congo Craton (and Nico Perez, Encantadas, Luis Alves crustal fragments); 3—Tonian granitoids generated during crustal extension; 4—Tonian mafic dykes; 5—Tonian oceanic crust; 6—Kaoko schist belt; 7—Dom Feliciano schist belt; 8—Granite Belt (magmatic arc granitoids); 9—arc related Ediacaran sediments; 10—syncollisional granitoids; 11—Foreland basin deposits; 12—late-stage 529 Ma Subida syenogranite; 13—South Atlantic oceanic crust

(2) the late-Ediacaran detrital zircon population in the supracrustal sequences of the western portion of the Kaoko, Gariep and Saldania belts and in the Rocha Group were probably derived from the above magmatic arc; (3) the Dom Feliciano Schist Belt represents the passive margin deposits that accumulated on the eastern margin of the South American cratons and on the plate that eventually became subducted; (4) the late Ediacarian synorogenic units in the Porongos Group register a second stage of sedimentary deposition in DFB owing to the magmatic arc collision against the DFB passive margin deposits around 600 Ma; and (5) the estimated time for the existence of the Adamastor Ocean would be 180 myr from first oceanic crust formation at *c*. 780 Ma to its closure around 600 Ma.

In addition to the above points, but equally important for the proposed tectonic model, is the finding that the upper units and mafic rocks of the Marmora Terrain in the Gariep Belt in southwestern Africa bear many similarities to those of the Rocha Group and Paso del Dragón Formation mafic-ultramafic rocks in northeastern Uruguay and are likely to represent the same original basin (Will et al. 2014).

Eastward subduction of Adamastor oceanic crust explains the positions of the 640–600 Ma Florianópolis-Pelotas-Aiguá granitoid belt (magmatic arc) and the passive margin reflected by the Brusque-Porongos-Lavalleja groups located between that arc and the Rio de la Plata/Paranapanema cratonic margins, as well as the back-arc domains of the Kaoko-Gariep-western Saldania belts (Basei et al. 2005, 2008a; Frimmel et al. 2011, 2013). The Major Gercino-Cordilheira-Sierra Ballena lineament represents the Neoproterozoic suture that separates the terranes with African and South American affinities. Around 535 Ma, crustal shortening in the region came to a close when folding and thrusting reached the foreland basins of the Kaoko-Gariep-western Saldania belts and the Dom Feliciano Belt. Thus the history of the Adamastor Ocean as suggested here reflects a complete Wilson Cycle.

3.5 Principle Tectonic Stages in the Evolution of the Adamastor Ocean

Figure 3.4 shows a diagram displaying the main steps related to the evolution of the Adamastor Ocean as well as the final shortening phase when the major faults zones began to present a predominant directional displacent and more vertical planes. The final step represents the present situation, with the rupture plane that generated the Atlantic Ocean developed predominantly along the eastern portion of the former Granite Belt—that is, along the corresponding back-arc basin (Marmora Basin).

3.5.1 Crustal Extension (980–780 Ma)

Although the Adamastor Ocean is considered to be one of the main products of Rodinia fragmentation, there is no direct evidence of its existence as there are no unequivocal remnants of corresponding oceanic crust recorded. All evidence is indirect and mainly in the form of significant marine deposits in the Neoproterozoic sedimentary successions on both the African and South American sides.

Age data on rift-related siliciclastic and bimodal volcanic rocks preserved in the Neoproterozoic schist belts from both Rio de la Plata/Paranapanema and Congo/Kalahari cratonic margins suggest a protracted continental rifting phase between 900 and 780 Ma (Frimmel et al. 1996; Hoffman et al. 1996; Basei et al. 2000; Pedrosa Soares and Alkmin 2011). However, considering the size of the area related to the Adamastor Ocean, it is likely that rifting was diachronous, with the period of 980–780 Ma covering different stages of crustal thinning that occurred simultaneously at different places.

On the African side, the granitoids of the Richtersveld Suite in the Gariep Belt with magmatic pulses at 835, 800 and 770 Ma are a good example of the magmatism associated with the taphrogenic phase (Frimmel et al. 2001). Ages between 880 and 820 Ma obtained on the Lufilian Belt, the eastern continuation of the Damara Belt, have also been attributed to continental rifting (Johnson et al. 2007; Frimmel et al. 2011). In the Kaoko Belt, a similar range of U–Pb ages (840–805 Ma) obtained on metavolcanic rocks of a bimodal suite in the Central Domain have been interpreted as dating continental rift magmatism (Konopásek et al. 2008). Further zircon age data of 770–710 Ma from amphibolite at the eastern side of the Three Palms Mylonite Zone (Konapásek et al. 2014) indicate that rift-related magmatism there continued into the Cryogenian Period.

For the northern Mantiqueira Province in the eastern part of South America, Pedrosa-Soares and Alkmin (2011) suggested several episodes of fissural magmatism in the Araçuaí Belt, which preceded the opening of the Adamastor Ocean. The oldest of these events would correspond to emplacement of 1000 Ma mafic dykes in the southern portion of Bahia State (Renné et al. 1990). A second event between 960 and 875 Ma is marked by the association of basic dykes and A-type granitoids (Machado et al. 1989; Silva et al. 2008; Queiroga et al. 2012; Castro 2014; Souza 2016). Alkaline magmatism between 730 and 700 Ma (Rosa et al. 2007, 2015) is the youngest event of this phase. In the central and southern portion of the Ribeira Belt, this taphrogenic phase can be associated with the emplacement of dykes and mafic bodies with ages between 900 and 800 Ma (Heibron and Machado 2003; Siga et al. 2009; Campanha et al. 2016).

A good example of Tonian magmatism associated with continental rifting in the south-southeastern part of Brazil is the mylonitic Parapente syenogranite, which pre-dates the deposition of the sediments of the Brusque Group at the northern end of the DFB. This syenogranite has a composition akin to A-type granite and yielded a U–Pb zircon age of 845 Ma (Basei et al. 2008b). Also in the same area, a 930 Ma deformed gabbro occurs (Basei et al. 2011b), which, together with the above syenogranite, evidences magmatism related to crustal thinning prior to volcanism and sedimentation in the Brusque Belt.

Large serpentinite bodies in the Pien region might represent remnants of the oceanic crust exhumed during the closure of the Adamastor Ocean branch that would have existed between the Luis Alves Craton and the Curitiba Block. Gabbro and norite occurring among these serpentinite bodies, with U–Pb zircon ages around 630 Ma (Harara 2001), suggest that the generation of this oceanic crust occurred in the Ediacaran. Arc-related calc-alkaline granitoids ranging in age between 614–610 Ma mark the onset of subduction (Harara et al. 2004).

On the other hand, in Rio Grande do Sul, remnants of oceanic crust of Tonian age were identified in two distinct sites associated with ophiolitic complexes. One of them is the mafic-ultramafic complex of the São Gabriel terrain and yielded ages of 900–850 Ma. The closure of that ocean would have occurred around 750 Ma with the generation of island arc granitoids (Gubert et al. 2016; Arena et al. 2016). The second site where oceanic crust was also identified is in the Capané Antiform area, where 750 Ma deformed mafic-ultramafic rocks were found interstratified in the Tonian metasedimentary successions of the Porongos Group of the DFB (Arena et al. 2017).

Crustal thinning in the course of continental rifting should have invariably led to an increase in the regional geothermal gradient resulting from a rise of the asthenospheric mantle. Partial melting of the lower crust, thus generating granitic melts and migmatites, and low P/T metamorphism, can be expected for this stage. On the African side, little evidence is recorded for this metamorphic overprint, except for the noted increase in metamorphic grade towards the west within the Kaoko Belt.

On the South American side, evidence for such Tonian metamorphism is recorded by rocks in the Punta del Este Terrane (PET) of eastern Uruguay (Preciozzi et al. 1999; Basei et al. 2011a; Masquelin et al. 2012). The Jaguarão Terrane in southeastern Rio Grande do Sul (Brazil) has been suggested to represent a continuation of the PET because of similarities in lithology and geochronology (Cruz et al. 2017).

The PET is the continuation into South America of the Gariep Belt and its Namaqua metamorphic basement in Namibia and South Africa. Correlation of the PET with the Namaqua Metamorphic Belt was initially proposed by Preciozzi et al. (1999) and confirmed by subsequent studies on the supracrustal rocks on both sides of the South Atlantic Ocean (Basei et al. 2000, 2005, 2011a; Frimmel et al. 2011, 2013; Masquelin et al.2012). The PET consists of a high-grade metamorphic gneissic to migmatitic basement, the Cerro Olivo Complex, and its low-grade supracrustal cover, the Rocha Group. This terrain, along with the Granite Belt, thus represents a remnant of the Kalahari Plate under which the Adamastor oceanic crust was subducted.

The Cerro Olivo Complex comprises orthogneisses, constituting the Cerro Bori unit, and paragneisses of the Chefalote unit (Masquelin 2000). The Chefalote migmatites and mafic granulites contain four distinct metamorphic assemblages, recording M2 peak-metamorphic conditions of 7–10 kbar and 830–950 °C on a clockwise P–T path (Gross et al. 2009). The tectonic evolution of this segment is characterized by Mesoproterozoic Namaqualand Metamorphic Complex-type rocks having been overprinted by several Neoproterozoic tectonometamorphic events (Masquelin 2000; Oyhantçabal et al. 2009a; Basei et al. 2011a; Lenz et al. 2011; Masquelin et al. 2012).

Tonian 850–760 Ma granitoids in the PET have been interpreted as products of either subduction (Lenz et al. 2011; Masquelin et al. 2012) or continental rifting (Oyhantçabal et al. 2009a). We prefer the latter interpretation because of the omnipresence of Namaqua-age zircon xenocrysts and inherited nuclei in dated zircon grains (Basei et al. 2011a; Lenz et al. 2011). It is proposed, therefore, that crustal thinning prior to the opening of the Adamastor Ocean led to decompression-induced anatexis of Namaqua-type basement and associated low P/T metamorphism along the western margin of the Kalahari continental plate. Remnants of this modified crust with Tonian granitoids can also be found within the Granite Belt, notably in the Pelotas and Florianópolis batholiths, where several 780–800 Ma tonalitic, dioritic and orthogneissic xenoliths have been observed (Silva et al. 1999; Frantz and Botelho 2000; Koester et al. 2008; Basei unpublished data).

Inversion from extension to compression occurred only in Ediacaran times, as evident from deformation and granulite-facies metamorphism in the PET (Gross et al. 2009; Masquelin et al. 2012). An age of 614 Ma for this stage of high-grade metamorphism is indicated by U–Pb data obtained on metamorphic zircon overgrowths around Tonain magmatic zircon cores (Oyhantçabal et al. 2009a). Metamorphic monazite ages from Chefalote Formation paragneisses corroborate syncompressional metamorphism and migmatite formation between 645 and 632 Ma (Basei et al. 2011a).

3.5.2 Drifting Phase (780–640 Ma)

Crustal thinning and continental rifting eventually led to continental break-up and first formation of oceanic crust at around 780 Ma. First evidence of subduction and thus onset of closure of the Adamastor Ocean at 640 Ma leaves at least 140 myr for the opening of this ocean. This would be enough time to generate an ocean as wide as the modern South Atlantic and to accumulate a thick pile of sediments (largely siliciclastic) on its margins.

Recent studies have revealed three major depositional episodes associated with the tectonic history of the Adamastor Ocean—that is, continental rifting, followed by marine deposits of sag basins (predominantly siliciclastic units), both associated with the main extension phases and sediment supply mainly from the adjacent cratons. During closure of the Adamastor Ocean, Ediacaran synorogenic deposits related to subduction (back-arc) and collisional phases are distinguished by their sediment derivation mainly from the Ediacaran magmatic arc (Basei et al. 2008a; Frimmel et al. 2013; Pertille et al. 2015b, 2017; Höfig et al. in revision).

The above scenario was built by compiling information from the different Neoprotezoic belts that occur on both sides of the South Atlantic (Ribeira, Dom Feliciano, Kaoko, Gariep and Saldania belts). However, it is not straightforward to assemble this puzzle because of intense deformation with tectonic imbrication, which makes it difficult to recognize and characterize the tectonic context that controlled the deposition of the various units. For most units the identification of their real tectonic setting remains precarious.

In many cases, the provenance and age of detrital zircon grains have been valuable tools in the characterization of the depositional tectonic context. Several authors have suggested the existence of two main periods for the filling of the Neoproterozoic Kaoko/Gariep paleobasins using changes in the sedimentary successions that suggest a depositional hiatus separating the rift basins from the subsequent thick marine siliciclastic deposits.

Most of the Neoproterozoic sedimentary successions on the African side are either rift graben fills or represent Ediacaran back-arc basins (Goscombe et al. 2003, 2005; Frimmel et al. 2011, 2013). In contrast, sedimentation in the DFB schist belts (Brusque, Porongos and Lavalleja) reflects a passive margin setting on the western side of the Adamastor Ocean. The influence of the magmatic arc on the sedimentary units of the DFB became significant only after the collision between the arc and the terranes located to the west, when the Ediacaran late synorogenic units were deposited. These units are well identified in the Porongos Group (Pertille et al. 2015a, b, 2017; Höfig et al. in revision).

3.5.3 Subduction and Magmatic Arc Formation (640–600 Ma)

The best geological record of the former existence of the Adamastor Ocean are the Granite Belt (Florianópolis-Pelotas and Aiguá magmatic arc) in South America and its equivalent, the Coastal Terrane, in northwestern Namibia (Basei et al. 2000; Goscombe et al. 2005; Goscombe and Gray 2007). Eastward subduction of the Adamastor oceanic crust must have begun prior to 640 Ma, which is the oldest age of granitoids in the magmatic arc that developed above the subduction zone.

The *c*. 1200 km long Granite Belt is composed of the Florianópolis, Pelotas and Aiguá batholiths. Remains of the metasedimentary cover occur in the three segments, with its best exposure in Santa Catarina, represented by paragneiss (with minor calcareous intercalations) and by the low-grade metasedimentary rocks of the Queçaba Formation. In the latter, the abundance of detrital zircon with ages of 900–1200 Ma suggests that the Namaqualand Metamorphic Complex of southwestern Africa as a likely sediment source (Basei et al. 2008a).

In Santa Catarina the Florianópolis Batholith exhibits three main lithological associations (Aguas Mornas, São Pedro de Alcantara and Pedras Grandes) that bear strong resemblance, both lithological and geochronological, to the rock associations defined by Philipp and Machado (2005) and Philipp et al. (2016a, b) for the Pelotas Batholith in Rio Grande do Sul. In Uruguay, the Aiguá Batholith has the same age range but presents greater uniformity, and its internal units have not been mapped in any greater detail yet.

In Santa Catarina, the oldest unit, Aguas Mornas, is composed of deformed meso- to leucocratic grayish granitoids, with composition ranging from quartz-monzonite, granodiorite to granite. Gabbro and diorite stocks and plutons are common. The intermediate suite, São Pedro de Alcantara, is the most voluminous, consisting predominantly of equi- to inequigranular grayish leucocratic granitoids. Among the porphyritic types, hornblende-biotite granodiorite to monzogranitic granitoids predominate. Enclaves of amphibolite, diorite and quartz-diorite are common. The youngest association, Pedras Grandes, is composed predominantly of pink leucocratic syeno- to monzogranitic granitoids. These rocks are equigranular to slightly porphyritic, medium-grained and texturally isotropic, and they are associated with felsic volcanic and volcaniclastic rocks and microgranite dykes.

The first two groups represent the least differentiated magmatites ($SiO_2 < 60$wt%), whereas the younger syenogranite and felsic volcanic rocks contain >73wt% SiO_2. A strong negative correlation between P_2O_5 and TiO_2 in granitoids of the Florianópolis Batholith suggests that fractional crystallization involving apatite was important (Basei et al. 2015). Negative correlation of SiO_2 with Sr and Ba (except for the Águas Mornas Complex) and positive correlation with Rb indicates that the fractional crystallization process involved a considerable volume of feldspar. Calc-alkaline and subalkaline compositions predominate. Some of the two older units are metaluminous whereas the younger ones are transitional between meta- and peraluminous (Basei et al. 2015).

Fractionation between light and heavy rare-earth elements is observed in all the granitoid suites, with the Pedras Grandes Suite showing the smallest fractionation and most intense negative Eu anomaly. Virtually all the analysed samples plot in the field defined as post-collisional granite, indicating strong contamination of the magmas in the arc by continental crustal material.

All available U–Pb zircon ages (LAICPMS and SHRIMP) for the entire magmatic arc cover a range from 640 to 590 Ma (Silva et al. 2005; Florisbal et al. 2012a, b; Basei et al.2015). The younger values were obtained from the late Pedras Altas syenogranite and the oldest from augen gneiss of the Águas Mornas association. Whole rock Sm–Nd model ages are between 1200 and 1600 Ma (Basei et al. 2008a). High initial $^{87}Sr/^{86}Sr$ (>0.708) and moderate negative epsilon Nd values are further strong support of continental crust contribution in the generation of the magmatic arc.

Thus the Florianópolis, together with its corresponding Pelotas and Aiguá batholiths, corresponds to the roots of a Neoproterozoic magmatic arc, with strong crustal signature. Basei et al. (2000, 2008a) suggested that, based on the Nd model ages, and detrital zircon age pattern of its sedimentary cover, this arc would have an isotopic affinity with the terrains on the African side and that its genesis was related to the consumption of an oceanic crust subducted towards the east under the Kalahari and Congo cratons.

The generation of the magmatic arc on the edge of the African cratons, in a setting similar to the modern Andean Orogen, implies that the greatest extension of the Adamastor Ocean was to the west of the arc. The incorporation of the magmatic arc into the Dom Feliciano Belt took place only in the Ediacaran, after closure of the Adamastor Ocean and continent–continent collision in the course of Western Gondwana assembly. Its current position in South America is the result of the opening of the Atlantic Ocean along the eastern edge of the arc, following the contact with the back-arc deposits that correspond to the westernmost deposits of the Kaoko, Gariep and Saldania belts in southwestern Africa (Basei et al. 2008a; Frimmel et al. 2011, 2013).

Considering that this magmatic arc was active for at least 40 myr, it can be concluded that the Adamastor Ocean had reached at least 2000 km in width, assuming an average subduction rate of 5 cm/year. This value was obtained only for the ocean that existed between the Kaoko and the DFB, not including the branches between the Luis Alves and Curitiba Terranes and the Ribeira Belt, which would imply a much larger ocean. However, the total width of the ocean could have been much greater, possibly as much as 6000 km, if one takes the entire timespan of some 100 myr for the opening of the ocean into account (and using the same rate of subduction). This is close to the value suggested by Meert (2003) based on paleomagnetic data from African and South American cratons.

The Coastal Terrane has been recognized as the African counterpart of the magmatic arc consisting of calc-alkaline mafic, intermediate and felsic granitoids of 660–620 Ma age and metasedimentary rocks whose sediment load was derived from the magmatic arc (Seth et al. 1998; Kröner et al. 2004; Goscombe et al. 2005; Goscombe and Gray 2007; Foster et al. 2015; Konapásek et al. 2016). There the arc-rocks are calc-alkaline granitoids, such as monzodiorite, granodiorite and monzogranite with minor amount of diorite, quartz diorite and gabbro. All of them were affected by high-grade metamorphism (Seth et al. 1998; Franz et al. 1999; Masberg et al. 2005).

The Coastal Terrane is considered an exotic domain when compared with the Kaoko Belt turbiditic units deposited on the Congo Craton margin (Goscombe et al. 2003, 2005; Goscombe and Gray 2007, 2008; Frimmel et al. 2011; Konapásek et al. 2014). Differences in sedimentary provenance, magmatism and metamorphism in relation to the other segments of the Kaoko Belt are observed. Despite these differences the isotopic signature of its magmatic rocks and the detrital zircon provenance of its metasedimentary rocks are good indicators of the African roots of this segment, whose origin is also linked to the attenuated margin of the Congo Craton. The tectonic contacts and thrusts along which the Coastal Terrane were emplaced onto the other Kaoko Belt domains resulted from crustal shortening of the Kaoko and Dom Feliciano belts that followed the collision between the African and South American cratons.

3.5.4 Continental Collision (~600 Ma)

The Adamastor Ocean was much larger to the western side of the magmatic arc developed along the border of southwestern African cratons. Final closure of this ocean culminated in the collision of the magmatic arc with the South American continental segments. This collision occurred in the Ediacaran and left behind the Major Gercino-Cordillera-Sierra Ballena Suture Zone along which the sedimentary succession from the western margin of the Adamastor Ocean was juxtaposed to magmatic arc granitoids.

The suture zone, which stretches over a strike length of some 1200 km, is marked by up to a few kilometres-thick mylonite zones that display dextral displacement in Santa Catarina (Passarelli et al. 2011) and sinistral displacements in Rio Grande do Sul and Uruguay (Oyhantçabal et al. 2009b, 2011; Philipp et al. 2016a, b). The opposite displacements that took place at the same time along the shear zone are interpreted to reflect local partitioning of the collision vectors related to the different shapes of the continental masses involved in the collision.

This collision, although diachronic along its length, would have occurred around 600 Ma as suggested by U–Pb zircon age data from mylonitic arc granites, as well as by K–Ar cooling ages of synkinematic micas (Basei et al. 2011b; Passarelli et al. 2011). Compared with the age of arc magmatism (640–590 Ma), continental collision and suturing took place close to the end of arc magmatism, but about 10 myr after this magmatic episode had reached its peak (~610 Ma). In the Schist Belt, contact metamorphism overprinted, however, main syncollisional S2 fabric evident in the supracrustal rocks.

In Santa Catarina, the geochronological and geochemical-isotopic information of the intrusive bodies in the Schist Belt, all of them with a remarkable crustal signature (São João Batista, Valsungana and Nova Trento suites), suggest that these granitoids were generated around 590 Ma as a result of the thickening of the crust and heat introduced into the area by the 600 Ma collision of the magmatic arc with the Schist Belt (Basei et al. 2011b; Hueck et al. 2016, unpublished data). The 10 myr difference between the collision and the emplacement of the granitoids in the middle of the supracrustal rocks underlying the arc may result from the time required for the generation of granitic melts and their rise to shallower crustal levels.

In Rio Grande do Sul, the Cordillera Suite is the best example of collision-related magmatism. It consists of deformed, peraluminous granites that are now in many places mylonitic (Koester et al. 2001a, b; Philipp et al. 2013), intrusives in the metasedimentary rocks of the Porongos Group that outcrop parallel to the suture zone that follows the tectonic contact between the Pelotas Batholith (magmatic arc) and the Schist Belt. U–Pb zircon ages of these granitoids are around 600 Ma (Koester et al. 2001c).

Correlation of magmatic arc granitoid emplacement and its collision with the Schist Belt was first suggested by Passarelli et al. (1993) through the identification of a gradational change of the magmatic fabrics to subsolid shear deformation associated with the development of the Major Gercino Suture Zone in Santa Catarina. In the Rio Grande do Sul, a similar relationship has been observed between the granitoids of the Pelotas Batolith and the Cordillera shear zone (Philipp et al. 2016a, b).

Considering the above scenario, the magmatic-arc granitoids related to the Florianópolis, Pelotas and Aiguá batholiths are pre- to syncollisional. On the other hand, the younger granitoids that correspond to the syenogranites of the Pedras Grandes and Dom Feliciano Suites, with ages around 590 Ma, must be post-collisional, generated by decompression melting of continental crust as a result of orogenic collapse.

The filling of the Kaoko and Dom Feliciano depositional basins continued to about 590–580 Ma in the course of synorogenic basin development associated with the collision of the magmatic arc with the schist belts. This process was also concomitant with the installation of the foreland basins in both belts (Prave 1996; Hoffmann et al. 1998, 2004; Foster et al. 2015; Pertille et al. 2015a,b, 2017; Höfig et al. in revision).

The stress field that prevailed during the closure of the Adamastor Ocean and subsequent continental collision remained active and was responsible for the transpressive system that reactivated the main pre-existing lineaments with predominantly sinistral movements in the African domains and dextral displacement in the South American counterpart. This accentuated the extrusion of the arc, its double vergence, and caused its displacement towards the south (Goscombe et al. 2005) (Fig. 3.5).

3.6 Final Remarks and Conclusions

The comparative analysis of the Dom Feliciano and Kaoko belts made it possible to establish a protracted Wilson Cycle for the birth and demise of the Adamastor Ocean, but not in the position originally suggested by Hartnady et al. (1985), passing through lithospheric thinning, passive margin development, subduction, magmatic arc generation, collision and crustal thickening.

Originally, the Adamastor Ocean was perceived as a kind of proto-South Atlantic, and the modern South Atlantic has been thought to have opened along the Pan-African suture along which the Rio de la Plata Craton and the amalgamated Congo and Kalahari cratons became welded together. Although this notion is still being upheld by many workers (e.g. Buiter and Torsvik 2014), evidence reviewed in this chapter rather supports a more recently proposed model of the modern South Atlantic having opened up not along a suture zone but along a former back-arc basin (Frimmel et al. 2011; Will and Frimmel 2018). Subduction, which had led to the development of a large Andean-type magmatic arc,

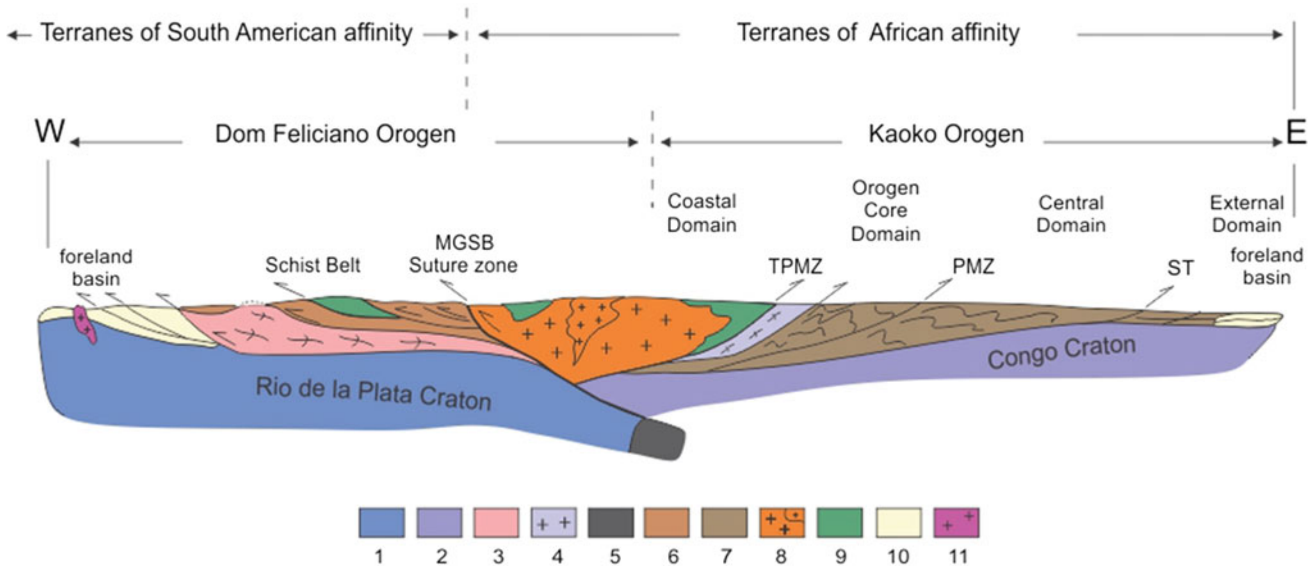

Fig. 3.5 Idealized cross-section juxtaposing Dom Felicano and Kaoko Belts: 1—Rio de la Plata Craton; 2—Congo Craton; 3—Encantadas, Luis Alves, Nico Perez crustal fragments; 4—tectonic exposures of basement belts inlier probably related to attenuated upper plate; 5—Adamastor oceanic crust remnant; 6—Dom Feliciano schist belt; 7—Kaoko schist belt; 8—Granite Belt (magmatic arc granitoids); 9—arc-related Ediacaran sediments; 10—Foreland basin deposits; 11—late stage 529 Ma Subida syenogranite

was not to the west but towards the east, implying the existence of a wide ocean, the redefined Adamastor Ocean, to the west of this magmatic arc. Integration of available data on the sedimentation history, magmatism and tectonometamorphic evolution of the various Neoproterozoic units of both sides of the modern South Atlantic, specifically the Dom Feliciano and Kaoko belts, revealed the following stages of a Wilson Cycle:

(1) Thinning and rifting of the Rodinia supercontinent, during the Tonian, with the climax of mafic dyke swarm emplacement, probably feeding a rift-related flood basalt province, around 850 Ma. This was followed by decompression- and mantle heat transfer-induced anatexis of the lower crust, the resulting emplacement of granitoids and formation of migmatites between 800 and 770 Ma. Evidence of this is best preserved in the PET in Uruguay. Transition from rifting to drifting occurred around 780 Ma. At the same time, further rift grabens opened to the east, along today's African west coast, but failed (see Chap. 13).
(2) Opening of the Adamastor Ocean lasted for at least 100 myr, and by 640 Ma subduction must have been well under way as evident from the oldest granitoids in the corresponding magmatic arc. Over this extended period of time, passive margin deposits accumulated on the margins of the Kalahari/Congo and Paranapanema/Rio de la Plata cratons.
(3) Peak of arc magmatism in the western edge of the Kalahari Craton was reached around 610–600 Ma. At the same time, a back-arc basin, the Marmora Basin, opened up east of the arc, probably reactivating pre-existing rift structures along the modern African west coast (see Chap. 13).
(4) Collision of the African cratons and the terranes of the South American portion began around 600 Ma shortly after the last manifestations of the magmatic arc, resulting in thickening of the continental crust along the Pan-African orogenic belts.

The importance of the magmatic arc in the structuring of the Kaoko and Dom Feliciano belts is striking, both because it represents the main product of the subduction process and because it formed, after collision, an important sediment source for the synorogenic deposits in both belts. The major tectonic boundaries are now present as important lineaments—that is, the Major Gercino-Cordilheira-Sierra Ballena Suture Zone in the DFB and the Three Palms Mylonite Zone in the Kaoko Belt. These doubly vergent shear zones were originally of low angle, being generated during the collision of Rio de La Plata and Congo cratons, progressing later to high-angle faults with directional movement owing to the crustal shortening process that followed the collision.

References

Affaton P et al (2016) The Pan-African West Congo belt in the Republic of Congo (Congo Brazzaville): stratigraphy of the Myombe and West Congo supergroups studied by detrital zircon geochronology. Precambr Res 272:185–202

Alkmim FF, Teixeira W (2017) The Paleoproterozoic Mineiro Belt and the Quadrilátero Ferrífero. In: Heilbron M et al (eds) São Francisco Craton, tectonic genealogy of a miniature continent. Springer, Eastern Brazil, pp 71–94

Almeida FFM (1965) Precambrian geology of North Eastern Brazil and Western Africa and the theory of Continental Drift. In: symposium on the granites of West Africa, Ivory Coast, Nigeria and Cameron. Proceedings, Paris: UNESCO, p 151–162

Almeida FFM et al (1981) Brazilian structural provinces: an introduction. Earth Sci Rev 17:1–29

Arena KR et al (2016) Evolution of Neoproterozoic ophiolites from the southern Brasiliano Orogen revealed by zircon U–Pb–Hf isotopes and geochemistry. Precambr Res 285:299–314

Arena KR et al (2017) U-Pb–Hf isotopes and trace elements of metasomatic zircon delimit the evolution of neoproterozoic Capané ophiolite in the southern Brasiliano Orogen. Int Geol Rev. https://doi.org/10.1080/00206814.2017.1355269

Assumpção M et al (2017) Lithospheric features of the São Francisco Craton. In: Heilbron M et al (eds) São Francisco Craton, tectonic genealogy of a miniature continent. Springer, Eastern Brazil, pp 15–25

Babinski M et al (2012) Neoproterozoic glacial deposits from the Araçuaí Orogen, Brazil: age, provenance and correlations with the São Francisco craton and West Congo belt. Gondwana Res 21:451–465

Barbosa JSF, Barbosa RG (2017) The Paleoproterozoic Eastern Bahia Orogenic domain. In: Heilbron M et al (eds) São Francisco craton, tectonic genealogy of a miniature continent. Springer, Eastern Brazil, pp 57–69

Basei MAS et al (1992) Evolução Tectonica dos Terrenos entre os Cinturões Ribeira e Dom Feliciano (PR e SC). Rev Bras Geoc 2:216–221

Basei MAS et al (1998) The Santa Catarina granulite complex of Southern Brazil, a review. Gondwana Res 1:383–391

Basei MAS et al (2000) The Dom Feliciano belt of Brazil and Uruguay and its foreland domain. In: Cordani U (ed) Tectonic evolution of South America, 31st International Geological Congress, Rio de Janeiro, Brazil, pp 311–334

Basei MAS et al (2005) A connection between the Neoproterozoic Dom Feliciano (Brazil/Uruguay) and Gariep (Namibia/South Africa) orogenic belts—evidence from a reconnaissance provenance study. Precambrian Res 139:195–221

Basei MAS et al (2008a) West Gondwana amalgamation based on detrital zircon ages from Neoproterozoic Ribeira and Dom Feliciano belts of South America and comparison with coeval sequences from SW Africa. Geol Soc Lond Spec Publ 294:239–256

Basei MAS et al (2008b) A-type rift-related granite and the lower Cryogenian age for the beginning of the Brusque Belt basin. In: Proceedings of South American symposium on isotope geology, vol 6, San Carlos de Bariloche, Argentina (CD-ROM)

Basei MAS et al (2009) The evolution and tectonic setting of the Luis Alves Microplate of Southeastern Brazil: an exotic terrane during the assembly of Western Gondwana. In: Gaucher C et al (eds) Special issue: Neoproterozoic-Cambrian tectonics, global change and evolution: a focus on Southwestern Gondwana Dev Precambriam Geol 16:273–291

Basei MAS et al (2010) Contribution of SHRIMP U–Pb zircon geochronology to unravelling the evolution of Brazilian Neoproterozoic fold belts. Precambrian Res 183:112–144

Basei MAS et al (2011a) The basement of the Punta del Este Terrane (Uruguay): an African Mesoproterozoic fragment at the eastern border of the South American Río de La Plata craton. Int J Earth Sci 100:289–304

Basei MAS et al (2011b) Tectonic evolution of the Brusque Group, Dom Feliciano Belt, Santa Catarina, Southern Brazil. J South Am Earth Sci 32:324–350

Basei MAS et al (2013) Polycyclic evolution of Camboriú Complex migmatites, Santa Catarina, Southern Brazil: integrated Hf isotopic and U–Pb age zircon evidence of episodic reworking of a Mesoarchean juvenile crust. Braz J Geol 43:427–443

Basei MAS et al (2015) Florianópolis Batholith—the roots of an Ediacaran Magmatic Arc generated during Gondwana Amalgamation, Dom Feliciano Belt, Santa Catarina State, South Brazil 2016 8th Hutton Symposium on Granites and Related Rocks. Florianópolis, Brazil, Abstracts, p 180

Brentan F (2011) Unidades turmaliníferas do Grupo Brusque, Rio do Oliveira, Tijucas, SC. 41 p, (graduation monograph). Instituto de Geociências, Universidade de São Paulo—USP, Brazil

Brito Neves BB, Fuck RA (2013) Neoproterozoic evolution of the basement of the South-American platform. J S Am Earth Sci 47:72–89

Buiter SJH, Torsvik TH (2014) A review of wilson cycle plate margins: a role for mantle plumes in continental break-up along sutures? Gondwana Res 26:627–653

Caby R (2003) Terrane assembly and geodynamic evolution of central-western Hoggar: a synthesis. J Afr Earth Sc 37:133–159

Campanha GAC et al (2016) The Mesoproterozoic to early Neoproterozoic passive margin Lajeado Group and Apiaí Gabbro, Southeastern Brazil. Geosci Front 7:683–694

Campos Neto MC, Figueiredo MCH et al (1995) The Rio Doce Orogeny, Southeastern Brazil. J S Am Earth Sci 8:13–162

Castro MP (2014) Caracterização Geológica da Formação Capelinha como uma unidade basal do Grupo Macaúbas em sua área tipo, Minas Gerais. Unpublished MSc thesis, Universidade Federal de Ouro Preto, 146 pp

Chemale F (2000) Evolução geológica do Escudo Sul-Riograndense. In: Holz M, De Ros LF (eds) Geologia Do Rio Grande Do Sul. Universidade Federal do Rio Grande do Sul, Porto Alegre, pp 13–52

Cordani UG et al (2003a) From Rodinia to Gondwana: a review of the available evidence from South America. Gondwana Res 6:275–283

Cordani UG et al (2003b) Tearing up Rodinia: The Neoproterozoic palaeogeography of South American cratonic fragments. Terra Nova 15:350–359

Cordani UG et al (2010) On the origin and tectonic significance of the intra-plate events of Grenvillian-type age in South America: a discussion. J South Am Earth Sci 29:143–159

Cordani UG et al (2013) The significance of the Transbrasiliano-Kandi tectonic corridor for the amalgamation of West Gondwana. Braz J Geol 43:583–597

Cruz RF et al (2017) O Terreno Jaguarão: Caracterização de Novo Domínio Geológico no Sudeste do Rio Grande do Sul. In: X international symposium on tectonics, 4 pp (CD-ROM)

D'Agrela-Filho MS, Cordani UG (2017) The paleomagnetic record of the São Francisco-Congo Craton. In: Heilbron M et al (eds) São Francisco Craton, Tectonic genealogy of a miniature continent. Springer, Eastern Brazil, pp 305–320

Degler R et al (2017) Contrasting provenance and timing of metamorphism from paragneisses of the Araçuaí-Ribeiraorogenic system, Brazil: hints for Western Gondwana assembly. Gondwana Res 51:30–50

DeKock GS et al (2000) U–Pb and Pb–Pb ages of the Naauwpoort rhyolite, Kawakeup leptite and Okongava diorite: implications for

the onset of rifting and of orogenesis in the Damara belt, Namibia. Commun Geol Surv Namibia 12:81–88
De Waele B et al (2009) The geochronological framework of the Irumide Belt: a prolonged crustal history along the margin of the Bangweulu Craton. Am J Sci 309:132–187
De Wit M et al (1988) Geological map of sectors of Gondwana: reconstructed to their disposition ∼150 Ma. scale 1:10.000.000: Lambert equal area projection-centred at 20°S, 40°E. American Association of Petroleum Geologists, Tulsa, USA
Faleiros FM et al (2011) Ediacaran high-pressure collision metamorphism and tectonics of the southern Ribeira Belt (SE Brazil): evidence for terrane accretion and dispersion during Gondwana assembly. Precambr Res 189:263–291
Fernandez-Alonso M et al (2012) The Mesoproterozoic Karagwe-Ankole Belt (formely the NE Kibara belt): the result of prolonged extensional intracratonic basin development punctuated by two short-lived far-field compressional events. Precambr Res 216–219:63–86
Florisbal LM et al (2012a) Space–time relation of post-collisional granitic magmatism in Santa Catarina, Southern Brazil: U–Pb LA–MC–ICP–MS zircon geochronology of coeval mafic–felsic magmatism related to the Major Gercino Shear Zone. Precambr Res 216–219:132–151
Florisbal LM et al (2012b) Petrogenesis of syntectonic granites emplaced at the transition from thrusting totranscurrent tectonics in post-collisional setting: whole-rock and Sr–Nd–Pb isotope geochemistry in the Neoproterozoic Quatro Ilhas and Mariscal Granites, Southern Brazil. Lithos 153:53–71
Foster DA et al (2015) U–Pb age and Lu–Hf isotopic data of detrital zircons from Neoproterozoic Damara Sequence: implications for pre-Gondwana proximity of Congo and Kalahari. Gondwana Res 28:179–190
Fragoso Cesar ARS (1980) O Cráton do Rio de La Plata e o Cinturão Dom Feliciano no Escudo Uruguaio-Sul Riograndense, Camboriu, SC. In: An. XXXI Congresso Brasileiro de Geologia, pp 2879–2892
Frantz JC, Botelho NF (2000) Neoproterozoic granitic magmatism and evolution of the Eastern Dom Feliciano Belt in Southernmost Brazil: a tectonic model. Gondwana Res 3:7–19
Franz L et al (1999) Diachronous Pan-African granulite-facies metamorphism (650 Ma and 550 Ma) in the Kaoko Belt, NW Namibia. Eur J Mineral 11:167–180
Frimmel HE et al (2011) Neoproterozoic geodynamic evolution of SW-Gondwana: a southern African perspective. Int J Earth Sci 100:323–354
Frimmel HE et al (2013) A new lithostratigraphic subdivision and geodynamic model for the Pan-African western Saldania Belt, South Africa. Precambr Res 231:218–235
Frimmel HE et al (1996) New Pb–Pb single zircon age constraints on the timing of Neoproterozoic glaciation and continental break-up in Namibia. J Geol 104:459–469
Frimmel HE et al (2001) The Richtersveld Igneous Complex, South Africa: U–Pb zircon and geochemical evidence for the beginning of Neoproterozoic continental breakup. J Geol 109:493–508
Fuck RA et al (2008) Rodinia descendentes in South America. Precambr Res 160:108–126
Fuck RA et al (2017) The Northern Brasília Belt. In: Heilbron M et al (eds) São Francisco Craton, tectonic genealogy of a miniature continent. Springer, Eastern Brazil, pp 205–220
Ganade Araujo CE et al (2012) U–Pb detrital zircon provenance of metasedimentary rocks from the Ceará Central and Médio Coreaú domains, Borborema province, NE-Brazil: tectonic implications for a long-lived Neoproterozoic active continental margin. Precambr Res 206–207:36–51
Ganade Araujo CE et al (2014) Ediacaran 2500-km-long synchronous deep continental subduction in the West Gondwana Orogen. Nat Commun 5:5198
Ganade Araujo CE et al (2016) Rightening-up NE Brazil and NW Africa connections: New U–Pb/Lu–Hf zircon data of a complete plate tectonic cycle in the Dahomey Belt of the West Gondwana Orogen in Togo and Benin. Precambr Res 276:24–42
Goscombe BD, Gray D (2007) The Coastal Terrane of the Kaoko Belt, Namibia: outboard arc terrane and tectonic significance. Precambr Res 155:139–158
Goscombe BD, Gray D (2008) Structure and strain variation at mid-crustal levels in a transpressional orogen: a review of Kaoko Belt structure and the character of West Gondwana amalgamation. Gondwana Res Focus Paper 13:45–85
Goscombe BD et al (2003) Structure of the Kaoko Belt, Namibia: progressive evolution of a classic transpressional orogen. J Struct Geol 25:1049–1081
Goscombe BD et al (2005) Event geochronology of the Pan-African Kaoko Belt, Namibia. Precambr Res 140:1–41
Gray DR et al (2006) 40Ar/39Ar thermochronology of the Pan-African Damara Orogen, Namibia, with implications for tectonothermal and geodynamic evolution. Precambr Res 150:49–72
Gross AOMS et al (2009) Petrology and thermobarometry of mafic granulites and migmatites from the Chafalote Metamorphic Suite: new insights into the Neoproterozoic P-T evolution of the Uruguayan-Sul-Rio-Grandense shield. Precambr Res 170(157):174
Gruber L et al (2011) Proveniência de metassedimentos das sequências Arroio Areião, Cerro Cambará e Quartzo Milonitos no Complexo Metamórfico Porongos, Santana da Boa Vista. RS Pesqui Em Geociências 38:205–223
Gubert ML et al (2016) The Bossoroca Complex, São Gabriel Terrane, Dom Feliciano Belt, southermost Brazil: U–Pb geochronology and tectonic implications for the Neoproterozoic São Gabriel Arc. J S Am Earth Sci 70:1–17
Halinann SE, Mantovani SMM (1993) Structural framework of the Southern Brazilian shield: the perspective from gravity models. In: III International Geoph. Congress, vol 2. Anais. SBGF, RJ, pp 1078–1083
Halverson GP et al (2002) A major perturbation of the carbon cycle before the Ghaub glaciation (Neoproterozoic) in Namibia: prelude to snowball earth? Gechem Geophys Geosyst 3:1–24
Harara OMM (2001) Mapeamento e investigação petrológica e geocronológica dos litotipos da região do Alto Rio Negro (PR-SC): um exemplo de sucessivas e distintas atividades magmáticas durante o Neoproterozóico. Unpublished PhD thesis, Institute of Geosciences—University of São Paulo, 206 p
Harara OMM et al (2004) Neoproterozoic supra subduction zone (SSZ) ophiolitic rocks from Piên (PR), southern Brazil. Quarenta anos de geocronologia no Brasil. In: Boletim de Resumos N. 89
Hartmann LA et al (2003) Prolonged Paleoproterozoic magmatic participation in the Neoproterozoic Dom Feliciano Belt, Santa Catarina, Brazil, based on zircon U–Pb SHRIMP geochronology. J S Am Earth Sci 16:477–492
Hartmann LA et al (2004) Paleoproterozoic magmatic provenance of detrital zircons, porongos complex quartzites, Southern Brazilian shield. Int Geol Rev 46:127–157
Hartnady CJH et al (1985) Proterozoic crustal evolution in southwestern Africa. Episodes 8:236–244
Hauzenberger CA et al (2014) Termination of the Southern Irumide Belt, Tanzania: Zircon U/Pb geochronology. Precambrian Res 255:144–162
Heilbron M, Machado N (2003) Timing of terrane accretion in the Neoproterozoic-Eopaleozoic Ribeira orogen (SE Brasil). Precambr Res 125:87–112

Heilbron M et al (2017) The Ribeira Belt. In: Heilbron M et al (eds) São Francisco Craton, genealogy of a miniature continent Tectonic. Springer, Eastern Brazil, pp 277–302
Hoffman PF (1991) Did the breakout of Laurentia turn Gondwanaland inside out? Science 252:1409–1412
Hoffman PF et al (1996) Precise U–Pb zircon ages for early Damaran magmatism in the Summas Mountains and Welwitschia Inlier, northern Damara belt, Namibia. Commun Geol Surv Namibia 11:47–52
Hoffman PF et al (1998) A Neoproterozoic snowball earth. Science 281:1342–1346
Hoffmann KH et al (2004) U–Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: constraints on Marinoan glaciation. Geology 32:817–820
Höfig DF et al (accepted) Polyphasic evolution of the Porongos metamorphic complex, Dom Feliciano Belt, southernmost Brazil: implications for the assembly of southwestern Gondwana. Precambrian Res
Hueck M et al (2016) Origin and evolution of the granitic intrusions in the Brusque Group of the Dom Feliciano Belt, south Brazil: petrostructural analysis and wholerock/isotope geochemistry. J S Am Earth Sci 69:131–151
Hueck M et al (unpublished data) Tracking the sources and the emplacement of the Neoproterozoic granitic intrusions in the Brusque Group, Dom Feliciano Belt, South Brazil: LA-ICP-MS and SHRIMP U–Pb zircon geochronology coupled to Hf isotopic analysis
Hurley PM et al (1967) Test of continental drift by comparison of radiometric ages. A pre-drift reconstruction shows matching geologic age provinces in West Africa and Northern Brazil. Science 157:495–500
Janasi VA et al (2009) Associated A-type subalkaline and high-K calc-alkaline granites in the Itu Granite Province, Southeastern Brazil: petrological and tectonic significance. Canadian Mineral 47:1505–1526
Johnson SP et al (2005) A review of the Mesoproterozoic to early Palaeozoic magmatic and tectonothermal history of south-central Africa: implications for Rodinia and Gondwana. J Geol Soc Lond 162:433–450
Johnson SP et al (2007) Geochronology of the Zambezi supracrustal sequence, southern Zambia: A record of Neoproterozoic divergent processes along the southern margin of the Congo Craton. J Geol 115:355–374
Koester E et al (2001a) Geologia e Geoquímica de Granitóides sintectônicos à Zona de Cisalhamento Transcorrente Dorsal do Canguçu, Encruzilhada do Sul, RS. Revista Brasileira de Geociências 31(2):141–154
Koester E et al (2001b) Petrologia dos Granitóides sintectônicos à Zona de Cisalhamento Transcorrente Dorsal do Canguçu, Encruzilhada do Sul, RS. Revista Brasileira de Geociências 31(2):131–140
Koester E et al (2001c) SHRIMP U–Pb age for the emplacement of the Santana granite and Reactivation of the Porto Alegre Suture, southern Brazil. J S Am Earth Sci 14:91–99
Koester E et al (2008) U–Pb ages of Granitoids from Eastern Sul-Riograndense shield. In: VI South American symposium on isotope geology, San Carlos de Bariloche—Argentina, 8 pp
Konopásek J et al (2008) Neoproterozoic igneous complex emplaced along major tectonic boundary in the Kaoko Belt (NW Namibia)—ion probe and laser ablation ICP-MS dating of magmatic and metamorphic zircons. J Geol Soc Lond 165:153–165
Konopásek J et al (2014) Timing and sources of pre-collisional Neoproterozoic sedimentation along the SW margin of the Congo Craton (Kaoko Belt, NW Namibia). Gondwana Res 26:386–401
Konopásek J et al (2016) Linking the basement geology along the Africa-South America coasts in the South Atlantic. Precambrian Res 280:221–230
Kröner A, Cordani UG (2003) African and South American cratons were not part of the Rodinia supercontinent: evidence from field relationships and geochronology. Tectonophysics 375:325–352
Kröner S et al (2004) U–Pb and Pb–Pb zircon ages for metamorphic rocks in the Kaoko Belt of Northwestern Namibia: a Paleo- to Mesoproterozoic basement reworked during the Pan-African orogeny. S Afr J Geol 107:455–476
Lehmann J et al (2015) Structural and geochronological constraints on the Pan-African tectonic evolution of the northern Damara Belt, Namibia. Tectonics 35:103–135
Leite RJ et al (2007) The late-to postorogenic transition in the Neoproterozoic Agudos Grandes Batholith (Apiaí Domain, SE Brazil): constraints from geology, mineralogy, and U–Pb geochronology. J S Am Earth Sci 23:193–212
Lenz C et al (2011) U–Pb SHRIMP ages for the Cerro Bori Orthogneisses, Dom Feliciano Belt in Uruguay: Evidences of a 800 Ma magmatic and 650 Ma metamorphic event. Precambrian Res 185:149–163
Li ZX et al (2008) Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambr Res 160:179–210
Machado N et al (1989) Resultados preliminares da geocronologia U–Pb na Serra do Espinhaço Meridional. In: V Simpósio de Geologia de Minas Gerais. Belo Horizonte, SBG, Anais, pp 171–174.
Masberg P et al (2005) Major and trace element and isotopic (Sr, Nd, O) constraints for Pan-African crustally contaminated grey granite gneisses from the southern Kaoko belt, Namibia. Lithos 84:25–50
Masquelin HC (2000) A Evolução Estrutural e Metamórfica do Terreno Punta del Este, Sudeste Uruguaio. Unpublished PhD thesis, University of Rio Grande do Sul, Brazil, 350 pp
Masquelin HC et al (2012) The Cerro Olivo complex: a pre-collisional neoproterozoic magmatic arc in Eastern Uruguay. Int Geol Rev. 54:1161–1183
Meert JG (2003) A synopsis of events related to the assembly of eastern Gondwana. Tectonophysics 362:1–40
Miller RM et al (2009) Geodynamic synthesis of the Damara Orogen sensu lato. Neoproterozoic to early Palaeozoic evolution of the Southwestern Africa (In: Gaucher C et al (eds) Neoproterozoic-Cambrian Tectonics, global change and evolution: focus on southwestern Gondwana). Dev Precambrian Geol 16:231–235
Nascimento DB et al (2016) Stratigraphy of the Neoproterozoic Damara sequence in northwest Namibia: slope to basin sub-marine mass transport deposits and olistolith fields. Precambr Res 278:108–125
Nascimento DB et al (2017) Depositional ages and provenance of the Neoproterozoic Damara Supergroup (northwest Namibia): Implications on the Angola-Congo and Kalahari cratons connection. Gondwana Res 52:153–171
Oyhantçabal P et al (2009a) The Sierra Ballena Shear Zone in the southernmost Dom Feliciano Belt (Uruguay): evolution, kinematics, and deformation conditions. Int J Earth Sci (Geol Rundsch) 99 (6):1227–1246
Oyhantçabal P et al (2009b) Geochronological constraints on the evolution of the southern Dom Feliciano Belt (Uruguay). J Geol Soc Lond 166:1–11, 1075–1084
Oyhantçabal P et al (2011) The transpressional connection between Dom Feliciano and Kaoko Belts at 580–550 Ma. Int J Earth Sci (Geol Rundsch) 100:379–390
Passarelli CR et al (1993) Caracterização geométrica e cinemática da Zona de Cisalhamento Major Gercino e sua importância na compartimentação dos terrenos Pré-Cambrianos de Santa Catarina. Revista Brasileira de Geociências 23:234–241
Passarelli CR et al (2011) Deformation and geochronology of syntectonic granitoids emplaced in the Major Gercino Shear Zone, southeastern South America. Gondwana Res 17:688–703

Pedrosa Soares AC, Alkmin FF (2011) How many rifting events preceded the development of the Araçuaí-west Congo Orogen? Geonomos 19:244–251

Pedrosa Soares AC et al (2001) The Araçuaí West Congo orogeny in Brazil: an overview of a confined orogeny formed during Gondwanaland assembly. Precambr Res 110:30–323

Pedrosa Soares AC et al (2008) Similarities and differences between the Brazilian and African counterparts of the Neoproterozoic Araçuaí-West Congo Orogen. In: Pankhurst JR et al (eds) West Gondwana: Pre-Cenozoic Correlations across the South Atlantic region. Geol Soc Lond Spec Publ 294:153–172

Pertille J et al (2015a) Zircon U–Pb age constraints on the Paleoproterozoic sedimentary basement of the Ediacaran Porongos Group, Sul-Riograndense Shield, southern Brazil. J South Am Earth Sci 63:334–345

Pertille J et al (2015b) Origin of the Ediacaran Porongos Group, Dom Feliciano Belt, southern Brazilian Shield, with emphasis on whole rock and detrital zircon geochemistry and U–Pb, Lu–Hf isotopes. J South Am Earth Sci 64:69–93

Pertille J et al (2017) Reconstructing the Cryogenian-Ediacaran evolution of the Porongos fold and thrust belt, Southern Brasiliano Orogen, based on Zircon U–Pb–Hf–O isotopes. Int Geol Rev 6814:1–29

Philipp RP, Machado R (2005) The late Neoproterozoic granitoid magmatism of the Pelotas Batholith, southern Brazil. J S Am Earth Sci 19:461–478

Philipp RP et al (2004) Caracterização litológica e evolução metamórfica da porção leste do ComplexoMetamórficoBrusque, Santa Catarina. Rev Bras Geocienc 34:21–34

Philipp RP et al (2013) Peraluminous leucogranites of the Cordilheira suite: a record of Neoproterozoic collision and the generation of the Pelotas Batholith, Dom Feliciano Belt, Southern Brazil. J South Am Earth Sci 43:8–24

Philipp RP et al (2016a) Tectonic evolution of the Dom Feliciano Belt in Southern Brazil: geological relationships and U–Pb geochronology. Braz J Geol 46(Suppl 1):83–104

Philipp RP et al (2016b) SHRIMP U–Pb age and high temperature conditions of the collisional metamorphism in the Várzea do Capivarita complex: implications for the origin of Pelotas Batholith, Dom Feliciano Belt, southern Brazil. J S Am Earth Sci 66:196–207

Pimentel MM (2016) The tectonic evolution of the Neoproterozoic Brasília Belt, central Brazil: a geochronological and isotopic approach. Braz J Geology 46:67–82

Pisarevsky SA et al (2003) Models of Rodinia assembly and fragmentation. Geol Soc Lond Sp Publ 206:35–55

Porada H (1979) The Damara-Ribeira Orogen of the Pan-African-Brasiliano cycle in Namibia (Southwest Africa) and Brazil as interpreted in terms of continental collision. Tectonophysics 57:237–265

Porcher CC et al (1999) Idade SHRIMP em zircão: vulcanismo ácido do Complexo Metamórfico Porongos. I Simpósio de Vulcanismo e Ambientes Associados. Brazilian Geological Society, Gramado, Brazil, p 110

Prave AR (1996) Tale of three cratons: tectonostratigraphic anatomy of the Damara Orogen in northwestern Namibia and the assembly of Gondwana. Geology 24:1115–1118

Prazeres Filho HJ et al (2003) Litoquímica, geocronologia U–Pb e geologia isotópica (Sr–Nd–Pb) das rochas graníticas dos batólitos Cunhaporanga e Três Córregos na porção sul do Cinturão Ribeira, Estado do Paraná. Geologia USP, Série Científica 3: 51–70

Preciozzi F et al (1999) The Namaqua/Grenville terrane of eastern Uruguay. In: Proceedings of the II South American symposium on isotope geology. Actas, Cordoba (Argentina), pp 338–340

Queiroga GN et al (2012) Geologia e Recursos Minerais da Folha Nova Venécia SE 24-Y-B-IV, Espirito Santo, 1:1000.000. Belo Horizonte, CPRM, p 76

Ramos VA et al (2010) Pampia: a large cratonic block missing in the Rodinia supercontinent. J Geodyn 50:243–255

Renné PR et al (1990) 40Ar/39Ar dating of 1.0–1.1 Ga magnetizations from the São Francisco and Kalahari Cratons: tectonic implications for Pan-African and Brasiliano mobile belts. Earth Planet Sci Lett 101(2–4):349–366

Robb LJ et al (1999) The history of granulite-facies metamorphism and crustal growth from singlezircon U–Pb geochronology: Namaqualand, South Africa. J Petrol 40:1747–1770

Rosa MLS et al (2007) Neoproterozoic anaorogenic magmatism in the southern Bahia Alkaline Province of NE Brazil: U–Pb and Pb–Pb ages of the blue sodalite syenites. Lithos 97:88–97

Rosa MLS et al (2015) Idade Pb–Pb do stock Nefelina Sienito Serra da Gruta, Província alcalina do sul do Estado da Bahia. Sci Plena 11 (3):1–5

Saalmann K et al (2011) Multiple accretion at the eastern margin of the Río de la Plata craton: the prolonged Brasiliano orogeny in southernmost Brazil. Int J Earth Sci Geol Rundsch 100:355–378

Sanchez-Bettucci L et al (2001) Tectonic setting of the late Proterozoic Lavalleja Group (Dom Feliciano Belt), Uruguay. Gondwana Res 4:395–407

Sanchez-Bettucci L et al (2004) Mineralizations of the Lavalleja Group (Uruguay), a probable Neoproterozoic Volcano-Sedimentary Sequence. Gondwana Res 7(3):745–751

Santos TMB et al (2015) Diachronic collision, slab-break-off and long-term high thermal flux in the Brasiliano-Pan African orogeny: implications for the geodynamic evolution of the Mantiqueira Province. Precambr Res 260:1–22

Schukowsky W et al (1991) Estruturação dos terrenos Pré-Cambrianos da região sul do Brasil e oeste do Uruguai: um estudo por modelamento gravimétrico. Rev Bras de Geofísica 9(2):275–287

Seth B et al (1998) Archaean to Neoproterozoic magmatic events in the Kaoko belt of NW Namibia and their geodynamic significance. Precambr Res 92:341–363

Siga Jr O et al (2009) Magmatic records of lower Neoproterozoic and upper Neoproterozoic in Itaiacoca Belt (Parana–Brazil): zircon ages and Lithostratigraphy studies. Gondwana Res, pp 197–208

Silva LC et al (1980) História metamórfica do Grupo Brusque em SC e Análise comparativa entre as regiões do Russo e da Catinga. In: Anais XXXI Congr. Bras. Geol. Balneario Camboriu, Santa Catarina, vol 5, pp 2982–2995

Silva LC et al (1999) SHRIMP U/Pb zircon dating of Neoproterozoic Granitic Magmatism and collision in the Pelotas Batholith, Southernmost Brazil. Int Geol Rev 41(6):531–551

Silva LC et al (2002) Dataçoes U–Pb SHRIMP do vulcanismo felsico na Bacia Brusque, Orogeno Pelotas, SC. SBG, Congresso Brasileiro de Geologia, 41, Anais, João Pessoa, p. 510

Silva LC et al (2005) SHRIMP U–Pb zircon geochronology of Neoproterozoic crustal granitoids (Southern Brazil): a case for discrimination of emplacement and inherited ages. Lithos 82:503–525

Silva LC et al (2008) Tonian rift-related, A-type continental plutonism in the Araçuaí orogen, eastern Brazil: new evidence for the breakup stage of the São Francisco-Congo Paleocontinent. Gondwana Res 13:527–537

Souza MES (2016) Caracterização Estrutural e Geocronológica dos Xistos Verdes e Metagabros do Grupo Macaúbas na Faixa Terra Branca-Planalto de Minas, Minas Gerais. Federal University of Ouro Petro. Unpublished master's thesis 215 pp

Squire RJ et al (2006) Did the Transgondwanan supermountain trigger the explosive radiation of animals on Earth? Earth Planet Sci Lett 250:116–133

Tack L et al (2001) Early Neoproterozoic magmatism (1000–910 Ma) of the Zadinian and Mayumbian Groups (Bas-Congo): onset of Rodinia rifitng and the western edge of the Congo craton. Precambr Res 110:277–306

Tedeschi M et al (2016) The Ediacaran Rio Doce Magmatic Arc revisited (Araçuaí-Ribeira orogenic system, SE Brazil). J S Am Earth Sci 68:167–186

Teixeira AL et al (2004) Bacias do estágio de transição da plataforma sul-americana. In: Mantesso-Neto V, Bartorelli A, Carneiro CDR, Brito-Neves BB (eds) Geologia do Continente Sul-Americano—Evolução da obra de Fernando Flávio Marques de Almeida, capítulo 29. BECA, São Paulo, pp 487–536

Teixeira W et al (2013) U–Pb (ID-TIMS) Baddeleyite ages and paleomagnetism of 1.79 and 1.59 Ga tholeiitic dyke swarms, and position of the Rio de la Plata Craton within the Columbia supercontinent. Lithos 174:157–174

Teixeira W et al (2017) The nature and evolution of the Archean Crust of the São Francisco craton. In: Heilbron M et al (eds) São Francisco Craton, Eastern Brazil: tectonic genealogy of a miniature continent. Regional geology review series. Springer, Berlin, pp 29–56 (CH 3)

Tohver E et al (2006) Paleomagnetic record of Africa and South America for the 1200–500 Ma interval, and evaluation of Rodinia and Gondwana assemblies. Precambr Res 147(3–4):193–222

Tohver E et al (2010) Closing the Clymene ocean and bending a Brasiliano belt: evidence for the Cambrian formation of Gondwana, southeast Amazon craton. Geology 38:267–270

Trompette R (1997) Neoproterozoic ($\sim$600 Ma) aggregation of western Gondwana: a tentative scenario. Precambr Res 82:101–112

Unrug R (1997) Rodinia to Gondwana: the geodynamic map of Gondwana supercontinent assembly. GSA Today 7(1):1–6

Valeriano CM et al (2016) Cambro-Ordovician post-collisional granites of the Ribeira Belt, SE-Brazil: a case of terminal magmatism of a hot orogen. J S Am Earth Sci 68:569–581

Vlach SRF, Gualda GAR (2007) Allanite and chevkinite in A-type granites and syenites of the Graciosa Province, southern Brazil. Lithos 97:98–121

Will TM, Frimmel HE (2018) Where does a continent prefer to break up? Lessons from the South Atlantic margins. Gondwana Res 53:9–19

Will TM et al (2004) Barrovian and Buchan type metamorphism in the Pan-African Kaoko belt, Namibia: Implications for its geotectonic position within the framework of Western Gondwana. S Afr J Geol 107:431–454

Will TM et al (2014) Geochemical and isotopic composition of Pan-African metabasalts from southwestern Gondwana: evidence of Cretaceous South Atlantic opening along a Neoproterozoic back-arc. Lithos 202–203:363–381

Yamamoto MT, Basei MAS (2009) Geoquímica isotópica e idade U-Pb em zircão do magmatismo básico do Grupo Brusque no Estado de Santa Catarina, SC. Simpósio 45 anos de Geocronologia no Brasil, Boletim de Resumos Expandidos. São Paulo, Brasil, pp 328–330

Zvirtes G et al (2015) Evidências de rifteamento e metamorfismo orogênico nos estágios finais de evolução do Cinturão Dom Feliciano na Antiforme Capané, Cachoeira do Sul, RS. In: 9th South-Brazilian geological symposium. Brazilian Geological Society, pp 141