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

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Abstract: Neoproterozoic–Cambrian amalgamation of West Gondwana involved the collision of several terranes of older crust that are now in eastern South America and western Africa. U–Pb (SHRIMP) detrital zircon ages from representative metasedimentary units of the Ribeira and Dom Feliciano belts (South America) and Gariep and Damara belts (Africa) provide constraints on the possible sediment source areas across probable suture zones. Ribeira detrital zircons are Palaeoproterozoic and Archaean. For the Dom Feliciano Belt, a contribution of Meso- and Neoproterozoic zircons is present, which definitely indicate Neoproterozoic sedimentation. It is proposed that the inflow of material to the Ribeira basin was essentially derived from the Paranapanema and Rio de la Plata cratons, whereas for the Damara and Gariep–Rocha belts source areas were from the Namaqua Belt. The Dom Feliciano Belt received sediments from the South American side and to a lesser degree from African sources. These results highlight the differences in the detrital zircon signatures across a proposed West Gondwanan suture, with those in the west being derived from distinctive South American basement sources and those in the east from distinctive African sources.

Crustal evolution in southern Brazil involved the Neoproterozoic Brasiliano orogenic cycle with tectonic events that led to the amalgamation of different terranes during collisional orogeny, culminating in the formation of West Gondwana by the start of the Cambrian (Brito Neves & Cordani 1991; Campos Neto & Figueiredo 1995; Brito Neves *et al.* 1999; Campos Neto 2000). Ophiolitic remnants and magmatic arc roots signal the existence of fossil subduction and collision zones (Brito Neves *et al.* 1999; Campos Neto 2000; Basei *et al.* 2000). In this study, new SHRIMP U–Pb ages for detrital zircon grains from 11 samples from the major metasedimentary units of the Ribeira, Dom Feliciano and Damara belts of the southern portions of South America and South Africa are presented and compared to available analyses for the Kaoko (Goscombe *et al.* 2005) and Gariep (Basei *et al.* 2005) belts. A revised tectonic model is then presented for the formation of West Gondwana, based on the combination of these U–Pb ages with Sm–Nd bulk rock isotope data. These detrital zircon studies support the location of a suture based on other evidence.

Geological setting

The Precambrian–Cambrian geology of southeastern Brazil and Uruguay is marked by the presence of the Paranapanema and Rio de la Plata cratons in the western portion, which are now mostly

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covered by the Palaeozoic sediments of the Paraná Basin. These cratonic domains were the foreland during the Neoproterozoic evolution of the southern portion of the Ribeira Belt and the Dom Feliciano Belt (Fig. 1).

The granitic–migmatitic–granulitic rocks of the allochthonous Luís Alves and Curitiba terranes are continental fragments that separate the Ribeira and Dom Feliciano belts (Basei *et al.* 1999). They contain Archaean rocks with superimposed

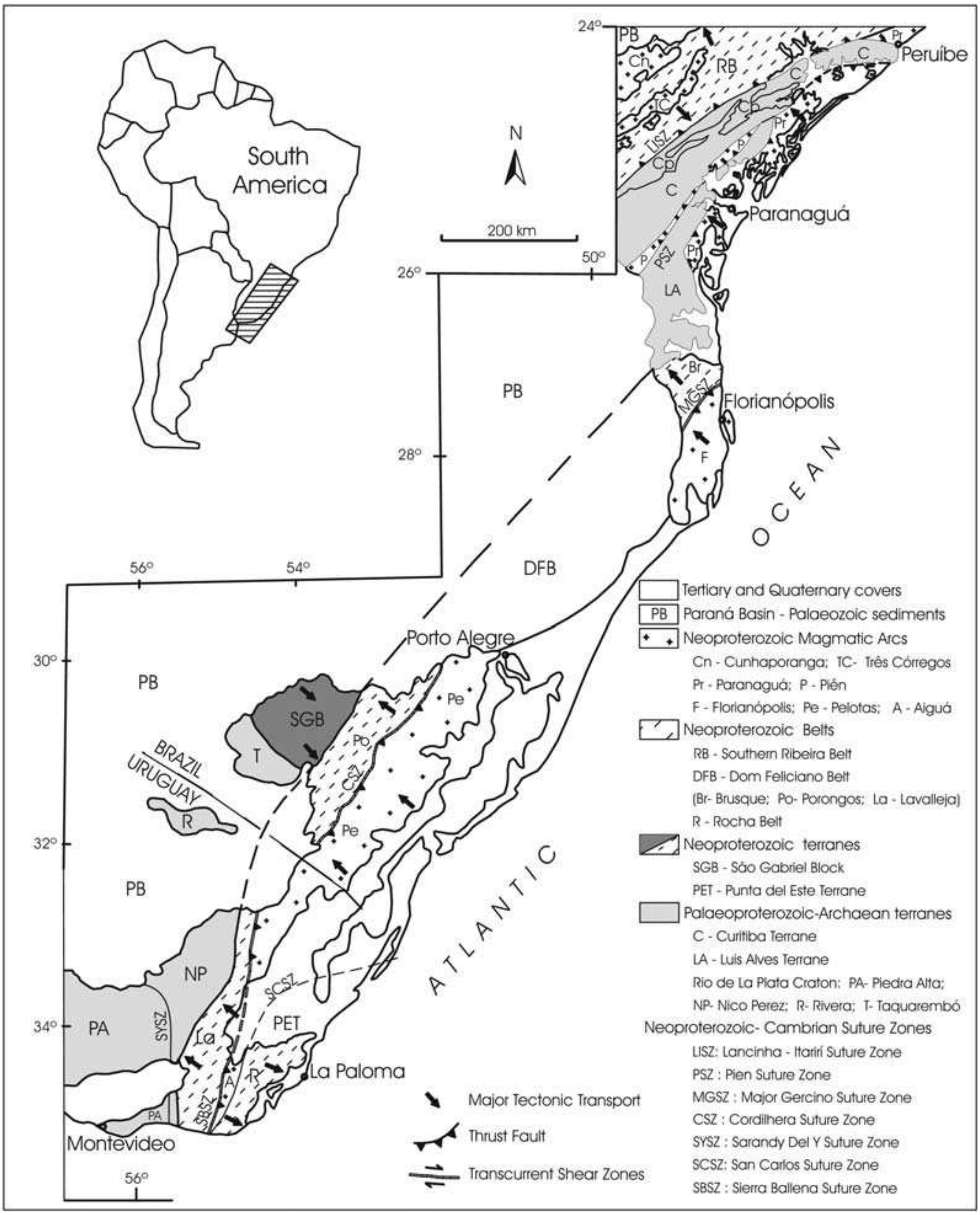

Fig. 1. Distribution of the main tectonic units of the southern Brazil and Uruguay (modified from Basei *et al.* 1999, 2000; Soares *et al.* 2000; Campos Neto 2000; Sanchez-Bettucci *et al.* 2004).

Palaeoproterozoic high-grade metamorphism (Basei *et al.* 1998). Despite the similarities between these continental blocks, the Luís Alves microplate escaped Neoproterozoic tectono-thermal overprint (Palaeoproterozoic K–Ar ages), whereas the Curitiba domain was intensely affected by Neoproterozoic migmatization and crustal melting during the Brasiliano orogeny (Basei *et al.* 1998).

The juxtaposition of the Luís Alves and Curitiba terranes involved the destruction of Neoproterozoic oceanic crust whose remnants are locally preserved in the Pien–São Bento do Sul region (Fig. 1; Harara 2001). Destruction of the oceanic domains at a convergent plate boundary included production of an extensive calc-alkaline granitoid batholith with magmatic arc affinities, which is now found associated with remaining dismembered ophiolitic, mafic–ultramafic complexes (Fig. 1).

Unmetamorphosed volcano-sedimentary basins are well represented by the Campo Alegre and Guaratubinha basins. They are spatially associated with the coeval A-type alkaline-peralkaline plutons (the Serra do Mar Suite). These reflect extensional events that took place in the Luís Alves and Curitiba terranes by the end of the Neoproterozoic (Siga *et al.* 1997, 1999).

The southern branch of the Ribeira Belt

The southernmost part of the Ribeira Belt is characterized by a series of NE–SW trending domains with Meso- to Neoproterozoic supracrustal rocks at low metamorphic grade, intruded by Neoproterozoic granitic batholiths and stocks (Campanha *et al.* 1985; Campanha & Sadowski 1999; Campos Neto 2000; Prazeres 2005). Most of these domains are separated by shear zones that have marked dextral horizontal displacements (Fiori 1992). This represents a polycyclic evolution, during which the Meso- and Neoproterozoic supracrustal units became juxtaposed. Neoproterozoic tectonothermal evolution is marked by northwestwards vergence towards the Paranapanema Craton (Mantovani & Brito Neves 2005). In contrast, Neoproterozoic transport in the southeastern portion of the belt was towards the Curitiba domain (Fiori 1992). From northwest to southeast, five major supracrustal domains are recognized: the Itaiacoca, Água Clara, Lageado, Votuverava and Capiru domains (Fig. 2).

The Itaiacoca Domain. This is an approximately 10 km wide, NE–SW elongated belt (Reis Neto 1994; Prazeres 2005) that occurs between the Cunhaporanga and the Três Córregos batholiths. It is marked by the Itaiacoca Group of shallow-water platform deposits of mostly meta-arkose with subordinate felsic metavolcanic rocks (Siga *et al.* 2003, 2006), plus a lower unit of stromatolitic dolomitic marble with some mafic rocks of volcanic origin (Reis Neto 1994). The NW border of the Itaiacoca Group is intruded by the Cunhaporanga batholith composed of granodiorite, monzogranite and quartz monzonite.

The Água Clara Domain. Lithologically, this domain consists of metacalcarenite, micritic metalimestone, meta-calcisiltite, calc-schist and subordinately mica schist, iron formation plus schists of probable volcanogenic origin (Fassbinder 1996; Weber *et al.* 2004). The regional metamorphism is of low amphibolite facies. The Três Córregos batholith intruded the Agua Clara sediments when they had already been deformed and metamorphosed (Janasi *et al.* 2001; Prazeres *et al.* 2005).

The Lageado Domain. This includes metaconglomerate, metasandstone, meta-rhythmite and calcitic marble of the Lageado Subgroup (Campanha *et al.* 1985) interpreted as shallow-water platform deposits, with alternating thick layers of carbonate and psammo-pelitic units. The metamorphic grade is greenschist facies. There are several post-tectonic granitic stocks, such as the Itaoca granite. The Iporanga and Antinha sedimentary units (Campanha *et al.* 1987; Campanha & Sadowski 1999) are here considered as the uppermost portion of the Lageado Subgroup.

The Votuverava–Perau Domain. The Votuverava Formation is composed of quartzite, rhythmic laminated phyllite, meta-siltite, meta-conglomerate, dolomitic marble, graphitic quartzite beds and metabasite lenses, all affected by greenschist facies metamorphism. These metasedimentary rocks interfinger with metabasic and volcaniclastic rocks and iron-manganese formations, from which a deep-water palaeo-environment is inferred (Fiori 1992; CPRM 1998). Again, post-tectonic Neoproterozoic granitic stocks occur, such as the Morro Grande, Cerne and Varginha intrusions. 2.2 Ga Palaeoproterozoic basement is represented by the Betara and Tigre gneissic–migmatitic nuclei (Cury *et al* 2002), exposed north of the Lancinha–Itariri suture zone (Basei *et al.* 1999).

The Capiru Domain. This comprises metasedimentary rocks covering the northern part of the Atuba Complex (Curitiba microplate), south of the Lancinha–Itariri suture zone (Figs 1 and 2). The Capiru Formation is composed of dolomitic marble (with stromatolite structures locally preserved), quartzite, and subordinated phyllite in the upper portions. Low-grade metamorphism (greenschist facies, chlorite zone) affected the Capiru Formation. Palaeoproterozoic migmatitic gneisses,

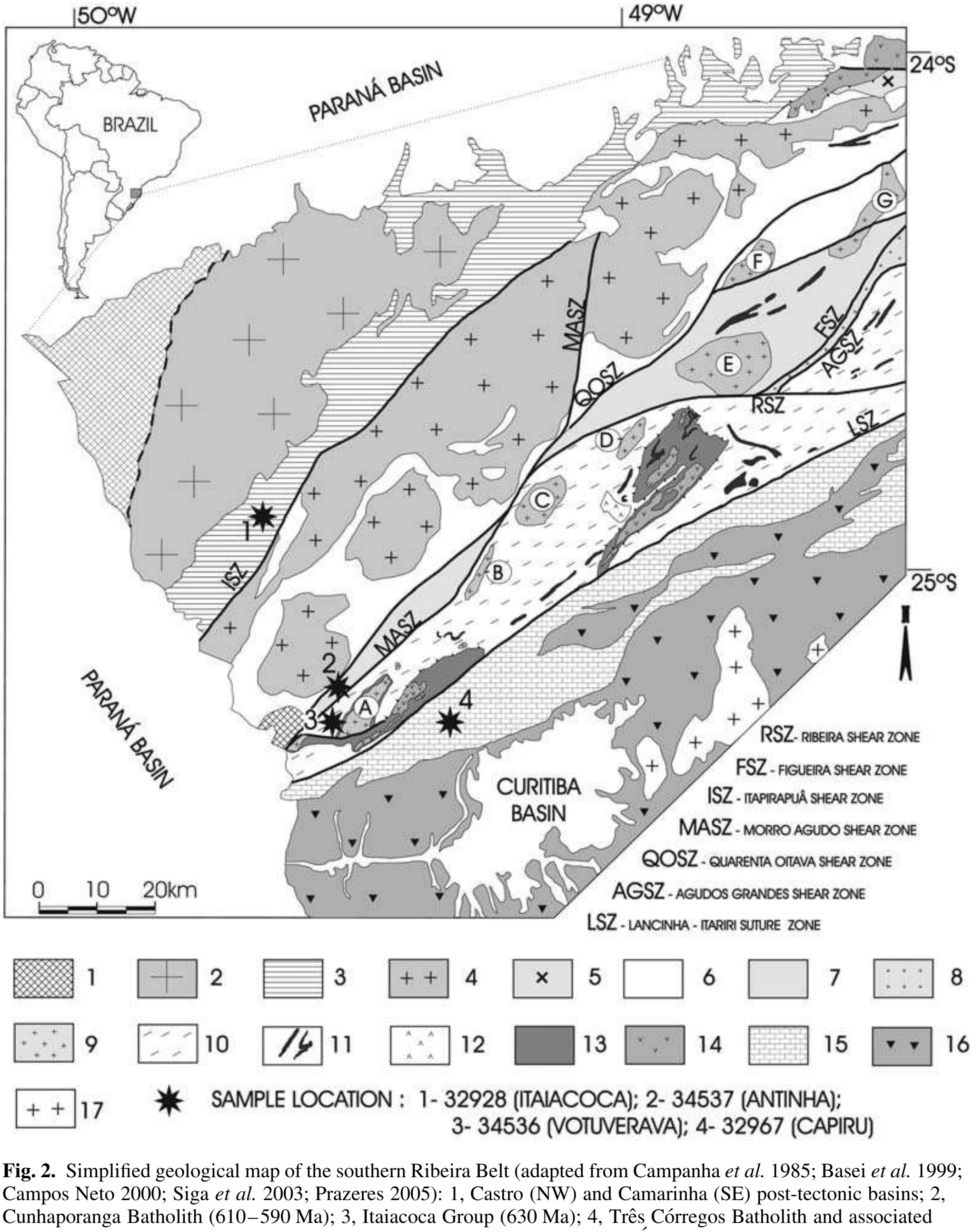

Fig. 2. Simplified geological map of the southern Ribeira Belt (adapted from Campanha *et al.* 1985; Basei *et al.* 1999; Campos Neto 2000; Siga *et al.* 2003; Prazeres 2005): 1, Castro (NW) and Camarinha (SE) post-tectonic basins; 2, Cunhaporanga Batholith (610–590 Ma); 3, Itaiacoca Group (630 Ma); 4, Três Córregos Batholith and associated granitic bodies (610–600 Ma); 5, A-type deformed granitoids (1750 Ma); 6, Água Clara Formation (*c.* 1450 Ma); 7, Lajeado Subgroup and Antinha Formation (*c.* 600 Ma); 8, Iporanga Formation (*c.* 590 Ma); 9, Syn- to post-collisional granitoids (590–570 Ma) (A, Cerne; B, Piedade; C, Morro Grande; D, Varginha; E, Itaóca; F, Apiaí; G, Espírito Santo); 10, Votuverava Formation (1450 Ma); 11, undifferentiated metabasic rocks (1450 Ma); 12, Tunas Syenite (85 Ma); 13, Perau and Betara formations (1450 Ma); 14, Basement inliers—deformed calc-alkaline granitoids (2200 Ma); 15, Capirú Formation (Neoproterozoic?); 16, Atuba Gneissic–Migmatitic Complex (2100 Ma); 17, alkaline–peralkaline granitoids of Serra do Mar Suite (595–570 Ma).

granites, amphibolites and mylonites of the Setuva Anticline are basement rocks correlated with the gneissic–migmatitic rocks of the Curitiba domain (Silva *et al.* 1998; Passarelli *et al.* 2003).

The Dom Feliciano Belt

The 1200 km long Dom Feliciano Belt has three domains (Fig. 3), here described from ESE to NNW. (i) The Eastern Granitoid Belt comprises the Florianópolis (Santa Catarina State), Pelotas (Rio Grande do Sul State) and Aiguá (Uruguay) granitic batholiths. They are all calc-alkaline in composition and represent the roots of a Neoproterozoic magmatic arc. (ii) The Supracrustal Schist Belt (central portion of the Dom Feliciano Belt) is predominantly composed of low-grade metavolcano-sedimentary units. It has been multiply folded, with northwestward tectonic transport, and was intruded by several generations of late- to post-tectonic granitoids that developed contact metamorphic aureoles. (iii) Foreland basins, less affected by deformation and metamorphism than the adjacent schist belt, are represented by the Itajaí Group (Santa Catarina State, Brazil), the Camaquã Basin (Rio Grande do Sul State, Brazil) and several fragments of similar basins that form the El Soldado Group (Uruguay).

The Supracrustal Schist Belt comprises all the metamorphic rocks located between the Eastern Granitic Belt and the foreland basins of the Dom Feliciano Belt (Fig. 3). It occurs discontinuously as a narrow belt with average width of around 40 km. From north to south, there are three metamorphic complexes within the supracrustal belt: Brusque (Santa Catarina State), Porongos (Rio Grande do Sul State) and Lavalleja (Uruguay).

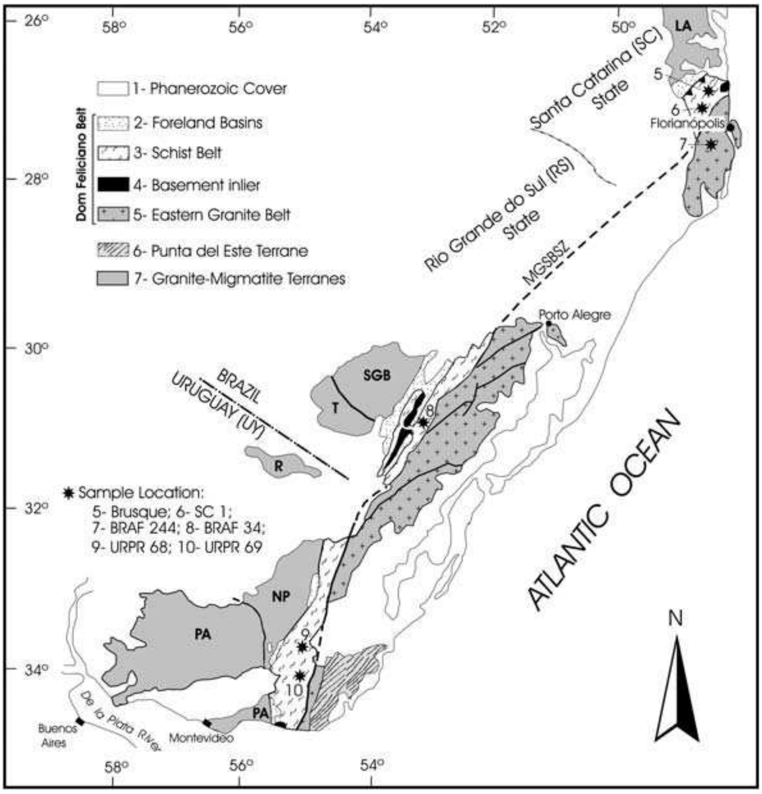

Fig. 3. Geological sketch of the Dom Feliciano Belt (modified from Basei *et al.* 2001): 1, Undifferentiated Phanerozoic cover; 2, Foreland basins (SC, Itajaí; RS, Camaquã; UY, El Soldado – Piriapolis); 3, schist belts and intrusive granitoids (SC, Brusque Metamorphic Complex; RS, Porongos Metamorphic Complex; UY, Lavalleja Metamorphic Complex); 4, reworked Palaeoproterozoic basement inliers (SC, Morro do Boi; RS, Encantadas; UY, Punta Rasa; 5, Eastern Granitoid Belt) (SC, Florianópolis; RS, Pelotas; UY, Aiguá batholiths); 6, Punta del Este Terrane; 7, Granite Migmatite Terranes (LA, Luis Alves; SGB, São Gabriel; R, Rivera; T, Taquarembó; NP, Nico Perez; PA, Piedra Alta.)

These complexes comprise poly-deformed sequences with at least three phases of folding associated with a northwestward tectonic transport that evolved to a predominantly lateral movement (Basei 1985; Fernandes *et al.* 1995; Basei *et al.* 2000). The regional metamorphic grade is greenschist to locally low amphibolite facies.

The Brusque Metamorphic Complex

This complex is composed of two metavolcano-sedimentary domains separated by the Valsungana batholith (Basei *et al.* 2000). In the northern segment, the sedimentary sequence starts with a pelitic–psammitic unit (now garnet-rich mica schist and quartzite) that grade to a psammo-pelitic unit (meta-rhythmites and homogeneous sericite schist), overlain by a metavolcano-sedimentary unit (meta-marl, calcareous schist, metabasic rocks and subordinate grey sericite schists (Basei 1985; Caldasso *et al.* 1995*a*, *b*). The mafic rocks represent syn-sedimentary basic magmatism of tholeiitic to alkaline affinity; structures produced by liquid immiscibility are frequently observed, characterizing them as variolitic basalt (Silva *et al.* 1985; Basei 1985; Sander 1992).

In the southern segment, the basal sequence is composed of a metavolcano-sedimentary unit that possibly represents the rift phase of the Brusque palaeo-basin (Basei *et al.* 2000). In this unit volcano-exhalative deposits are characterized by tourmalinites, associated with metabasalt, banded iron formation, quartzite (chert?) and calc-silicate rocks (Silva *et al.* 1985; Basei *et al.* 1994). Tectonically overlying is a thick psammo-pelitic sequence of micaceous quartzites, quartz–sericite schists and pelitic sericite schists where acid metavolcanic rocks occur locally. Granite magmatism is characterized by homogeneous to slightly deformed bodies of metaluminous to peraluminous composition whose genesis involved marked crustal contributions. They can be classified in three main suites, all post-dating much of the deformation and metamorphism in their host rocks (Castro *et al.* 1999).

The Porongos Metamorphic Complex

In Rio Grande do Sul State, the best exposures of the Porongos Metamorphic Complex are observed in the vicinity of Santana da Boa Vista Dome. They surround the Encantadas Gneisses in a Palaeoproterozoic basement inlier that forms the centre of an antiformal structure. The contact between the complex and the gneisses is tectonic (Jost 1981, 1982). The Porongos Metamorphic Complex contains a lower metasedimentary unit in which meta-arkose and impure quartzite predominate, intercalated with metapelite and rare amphibolite bodies. Quartzitic meta-rhythmites predominate in the intermediate portion, and mica schists form the top, with marble and orthoquartzite intercalations. The Porongos Metamorphic Complex also contains a metavolcanic sequence with meta-andesite, meta-dacite and several types of pyroclastic rocks. Subordinate, metachert, marble, metapelite, graphite schist and rare quartzite also occur (Jost 1981). The tectonic vergence is towards west, well observed in the eastern flank of the Santana Dome. These units were affected by medium pressure metamorphism (2.0–4.8 kbar) varying from chlorite zone (greenschist facies) to staurolite zone (amphibolite facies) (Jost 1982).

In the northern part of the Porongos Metamorphic Complex there is important magmatism dated at 780 Ma (Porcher *et al.* 1999). Its geochemical characteristics suggest evolution from a rift stage (alkaline gneisses) to a subduction stage (calc-alkaline acid volcanic rocks) associated with consumption of oceanic crust (Marques *et al.* 1998*a*, *b*). The Porongos complex supracrustal rocks are also intruded by the Campinas Granitic Suite. These granites occur as small stocks in the eastern part of the schist belt. They are mostly equigranular, isotropic, two-mica leucogranites showing a peraluminous trend, which suggests the involvement of the upper crust in their generation (Frantz & Jost 1983).

The Lavalleja Metamorphic Complex

In Uruguay, the Lavalleja Metamorphic Complex represents the southern extension of the Dom Feliciano Belt supracrustal rocks. It is subdivided from east to west into the Zanja del Tigre, Fuente del Puma and Minas formations (Sanchez-Bettucci 1998). The metamorphic grade decreases from east to NW, from lower amphibolite to sub-greenschist facies.

The Zanja del Tigre Formation is a metavolcano-sedimentary sequence in which gabbro and amphibolite occur within micaschists, garnet-rich schists and marbles. The overlying Fuente del Puma Formation consists of meta-conglomerate, calc-arenite, calcitic dolomite and mica schists, but with lesser amounts of volcanic and hypabyssal components (Sanchez-Bettucci 1998). The Minas Formation only contains metasedimentary rocks, with metapelite, quartzite, meta-arkose and stromatolite-bearing limestones. Some rocks attributed to the Lavalleja Group by Sanchez-Bettucci (1998) are now considered on the basis of fossil content to be younger, and have been correlated with the Vendian El Soldado Group (Gaucher 2000; Gaucher *et al.* 1996, 2004).

As observed in the Brusque Belt in Santa Catarina State, the Lavalleja supracrustal rocks were also intruded by abundant and chemically diverse granites (Mallmann *et al.* 2003; Sanchez-Bettucci *et al.* 2004). The largest bodies are the Maldonado intrusion into the Fuente del Puma Formation, and the Penitente intrusion in the Zanja del Tigre Formation.

Detrital zircon provenance

This study was undertaken to provide a 'fingerprint' of zircon provenance ages in metasedimentary rocks across the whole Neoproterozoic orogen, and thereby identify or confirm fundamental sutures. Due to budgetary constraints, it was only possible to analyse about 20 zircons from each of the eleven samples investigated, rather than the usual target of about 60 grains. With 20 grains analysed, there is a 95% probability of detecting age components present at the 15% level in the detrital zircon population. We consider this adequate for our orogen-wide reconnaissance study.

Sample collection was concentrated in typical units for each belt/unit. As the study aimed to reveal the general picture of the provenance of zircons, we tried to preserve all the different zircon morphologies during crystal concentration and handpicking, including crystal fragments. Zircon separation by standard gravimetric and isodynamic techniques and the mounting of selected zircons into epoxy resin discs were carried out at the Institute of Geological Sciences, University of São Paulo. Cathodoluminescence (CL) imaging and age determinations by SHRIMP took place in the Research School of Earth Sciences, The Australian National University, according to standard procedures (Compston *et al.* 1984; Williams 1998; Stern 1998; Sircombe 2000).

Choice of SHRIMP analytical sites was guided by CL imaging (McClaren *et al* 1994). All SHRIMP zircon analyses are available online at http://www.geolsoc.org.uk/SUP18290. A hard copy can be obtained from the Society Library. Most of the data yielded close to concordant ages. The data are portrayed graphically as histograms, with cumulative frequency curves shown in the background. These figures were generated in the program Isoplot/Ex (Ludwig 2001). The data were filtered prior to plotting, to remove analyses with the most disturbed radiogenic Pb-systematics. This removed analyses that were $<90\%$ concordant (if >1.0 Ga) and with $>2.5\%$ ^{206}Pb of common origin (calculated from measured ^{204}Pb using Cumming & Richards' (1975) Pb evolution curves for common Pb compositions). For grains with ages >1.0 Ga the ^{207}Pb/^{206}Pb age was plotted, whereas for grains <1.0 Ga the ^{206}Pb/^{238}U age was chosen.

The Ribeira Belt

Four of the five main units that compose the southern Ribeira Belt were studied. These are distributed along a NW–SE trend, including the Itaiacoca, Lageado (Iporanga–Antinha), Votuverava and Capiru units. Sample locations are indicated in Figure 2. Figure 4 shows representative CL images, and ages are displayed in Figure 5.

An arkosic quartzite belonging to the Abapã unit represents the Itaiacoca Group (sample 32928, UTM 619250 W; 7241755 S). Two Archaean grains (dated at 3.2 and 3.5 Ga) were detected, whereas the remainder are Palaeoproterozoic (1.9–2.2 Ga). No Neoproterozoic grains were encountered. On the other hand, the volcanic rocks of the same unit have mostly *c.* 630 Ma zircons that are interpreted as the age of zircon crystallization and consequently the age of deposition of the sedimentary units (Siga *et al.* 2005).

The Iporanga (SP) and Antinha (PR) formations of the Lageado Subgroup were studied. A metamarl of the Antinha unit (sample 34537, UTM 634677 W; 7201947 S) yielded Palaeoproterozoic zircons (1.8–2.2 Ga) with an age similar to that obtained for the detrital zircons of the Itaiacoca Group sample. Four grains of 0.59–0.61 Ga were dated, which are probably of volcanogenic origin (detail in Fig. 4). These data place the sedimentation of the unit in the Neoproterozoic. This age is similar to the age of the Iporanga Formation (Campanha *et al* 2006.) in São Paulo State, which is stratigraphically correlated with the Antinha Formation. The Votuvera Group is represented by a typical rhythmic psammo-pelitic phyllite (sample 32970, UTM 644976 W; 7203750 S). Two Archaean ages were obtained (3.2 and 2.8 Ga), two *c.* 2.4 Ga ages, a main group between 2.2 and 1.9 Ga and two ages close to 1.75 Ga. A Capiru Formation quartzite (sample 32967, UTM 671500; 7206625) gave an essentially unimodal zircon population at *c.* 2.2 Ga.

The Dom Feliciano Belt

Five samples representing the three metasedimentary units of the Dom Feliciano Belt were analysed: two from Brusque (Santa Catarina State), one from Porongos (Rio Grande do Sul) and two from Lavalleja (Uruguay). Sample locations are indicated in Figure 3, ages are summarized in Figure 6, and Figure 7 shows representative CL images.

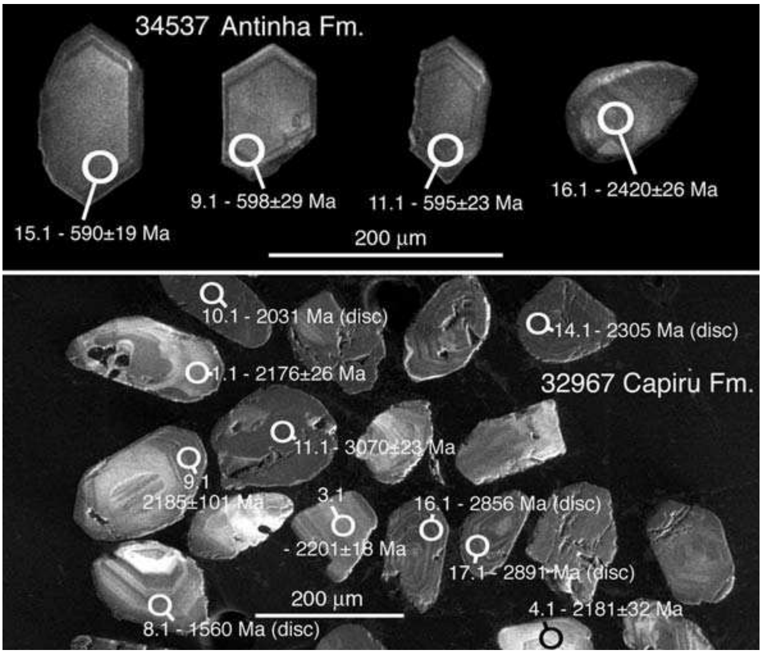

Fig. 4. Cathodoluminescence images of Ribeira Belt zircon grains. The detail shows the characteristics of the Antinha Formation volcanogenic zircon grains.

For the Brusque Metamorphic Complex, 22 zircon dates were obtained for a mica schist with a volcanogenic contribution (sample SC1, UTM 702267 W; 6977450 S) and a garnet–biotite schist (sample 32929, UTM 694676 W; 6992222 S), shown collectively as 'Brusque' on Figure 7. These yielded eight grains between 2.25 and 1.7 Ga, six between 1.5 and 1.3 Ga, four between 1.3 and 1.1 Ga and two between 0.54 and 0.57 Ga. Note the presence of Mesoproterozoic ages and the lack of Archaean ones.

For the Porongos Metamorphic Complex in Rio Grande do Sul State, 23 zircons were dated from a sericitic phyllite, BRAF 34. The sample was collected along the Pelotas–Caçapava highway, close to the bridge over the Rio Camaquã (UTM 298238 W; 6579203 S). Four age groups are present, with eight grains between 2.2 and 1.7 Ga, three between 1.5 and 1.4 Ga, six between 1.3 and 0.9 Ga and five Neoproterozoic grains in the 0.62–0.99 Ga interval (three of which are between 0.62 and 0.70 Ga).

From the Lavalleja Metamorphic Complex two samples were analysed. Quartz–sericite schist of the Fuente del Puma (sample URPR 68, Lat 34°29′25″ S; Long. 55°13′01″ W) was collected from a well-exposed outcrop on Road 60. A broad range of zircon ages was obtained: seven Archaean (2.6–3.4 Ga), six between 1.78 and 2.4 Ga, and five Neoproterozoic ages between 0.60 and 1.06 Ga, with three values close to the youngest age.

For the Zanja del Tigre Formation, considered by Sanchez-Bettucci (1998) as belonging to the Lavalleja Metamorphic Complex, a sample from a rhythmic meta-psammitic rock was collected on Road 12 (sample URPR 69, Lat 34°33′13″ S; 55°05′26″ W). For this sample, eight Archaean grains were found (four >3.0 Ga) and the others were all 1.8–2.3 Ga. A sole 1.4 Ga age was not taken into account, due to the uncertainty associated with its high degree of discordance. Thus, no definite Meso- or Neoproterozoic zircons were found in this sample.

Overview of the detrital zircon ages

Approximately 2.2 Ga detrital zircon is an important component in all of the Ribeira Belt samples. For two samples, ages older than 3.0 Ga were detected from the NW (Itaiacoca) and the SE (Capiru) borders of the belt. Only the Antinha Formation sample yielded *c.* 0.60 Ga zircon ages (interpreted as a volcanogenic contribution). The bimodal pattern of *c.* 2.2 Ga and some older zircon ages is characteristic of the Precambrian domains constituting the Paraná Basin basement in southeast Brazil (Bossi *et al.* 1992, 2004;

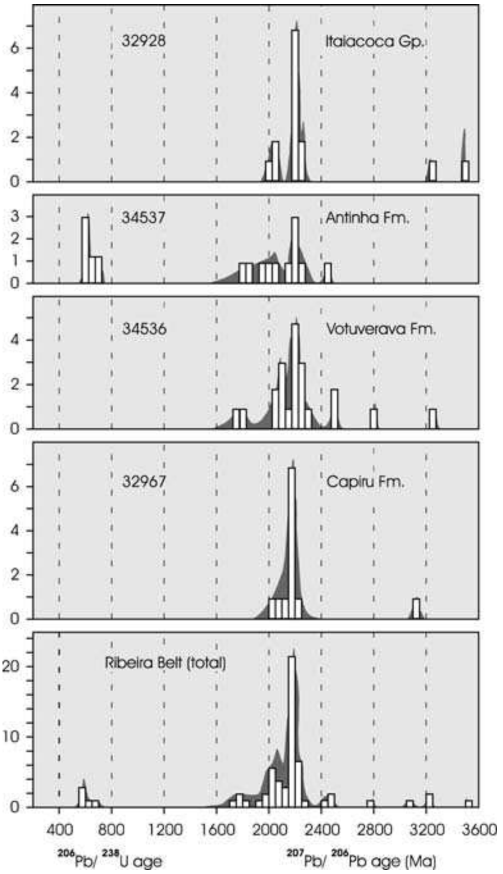

Fig. 5. Histogram of SHRIMP U–Pb and Pb–Pb ages for the Ribeira Belt detrital zircons. The lack of detrital zircons of Mesoproterozoic age is striking. The Neoproterozoic values are due to crystals of volcanic origin.

Hartmann *et al.* 1999, 2000*a*, *b*, *c*, 2001, 2003, 2004; Silva *et al.* 1999, 2000, Mallmann *et al.* 2003; Sanchez-Bettucci *et al.* 2004; Basei *et al.* 2000, 2005). As discussed below, the lack of 1.0–1.3 Ga Mesoproterozoic grains in the Ribeira Belt units is a striking feature.

The results for the Dom Feliciano Belt are similar to those for the Ribeira Belt and show that the Archaean–Palaeoproterozoic terranes were important sources. On the other hand, the *c.* 1.2 Ga Mesoproterozoic detrital zircons of the Dom Feliciano Belt stand out, because source areas of this age are unknown in southeastern Brazil. Moreover, for the sediments of the Lavalleja unit, approximately half of the grains have ages of 2.7–3.5 Ga, and as yet there has been no positive identification of source terranes of this age in southeastern Brazil and Uruguay.

In the three segments of the Dom Feliciano Belt, Neoproterozoic ages were observed, showing that deposition of a great part of the sequences took place during the Neoproterozoic Brasiliano cycle. This resolves a long-lasting controversy over the timing of their deposition.

Comparison with southwestern Africa

The geology of southwestern Africa is marked by the Kaoko, Damara, Gariep and Saldania Neoproterozoic belts (Fig. 8). Except for the internal Damara branch, these belts are parallel to the coast, defining the western margins of the Congo and Kalahari cratons (Fig. 8). In the Gariep Belt, *c.* 0.75 Ga and *c.* 0.58 Ga glacial events have been recognized (Frimmel *et al.* 2002), and the remains of a Neoproterozoic ocean floor have been identified in the Marmora terrane (Frimmel *et al.* 1996). The kinematic history of the Gariep Belt is characterized by nappe and thrust systems with east-southeastward tectonic transport, towards the Kalahari Craton. The maximum age of sedimentation for the basal continental rift phase is 771 ± 6 Ma, which is the youngest U–Pb single zircon age yet obtained from the underlying basement (Frimmel *et al.* 2001). Ar–Ar ages around 575 and 525 Ma, obtained on hornblende and micas, record an early, probably accretion-related metamorphic pulse and the peak of continental collision, respectively (Frimmel 1995; Frimmel & Frank 1998). Post-tectonic alkaline magmatism affected the central part of the belt. The best constraint available on the timing of this magmatism stems from a U–Pb single zircon age of 505 ± 6 Ma, obtained from the largest of the intrusive bodies, the Kuboos granite pluton (Frimmel *et al* 1996).

The ages of Gariep Belt detrital zircons were presented by Basei *et al.* (2005). That study was carried out on samples from the basal and outermost quartzite unit (Stinkfontein Subgroup) and from siliciclastic phyllites of the Oranjemund Formation, which represents syn-orogenic foredeep deposits that were laid down on top of, and in front of, the advancing oceanic crust now preserved as fragments in the Marmora terrane (Frimmel & Foelling 2004). These data are incorporated in the histogram of Figure 9, which also contains unpublished ages from rocks of the Damara Belt. The age pattern for the Gariep detrital zircons indicates that 1.0–1.2 Ga terranes were the main source areas. A few 0.6–0.8 Ga grains were detected in the samples both from the external and internal parts of the belt. This suggests that despite the lithological contrasts, the same detritus sources remained available for these two sectors. Detrital zircons with *c.* 0.6 Ga

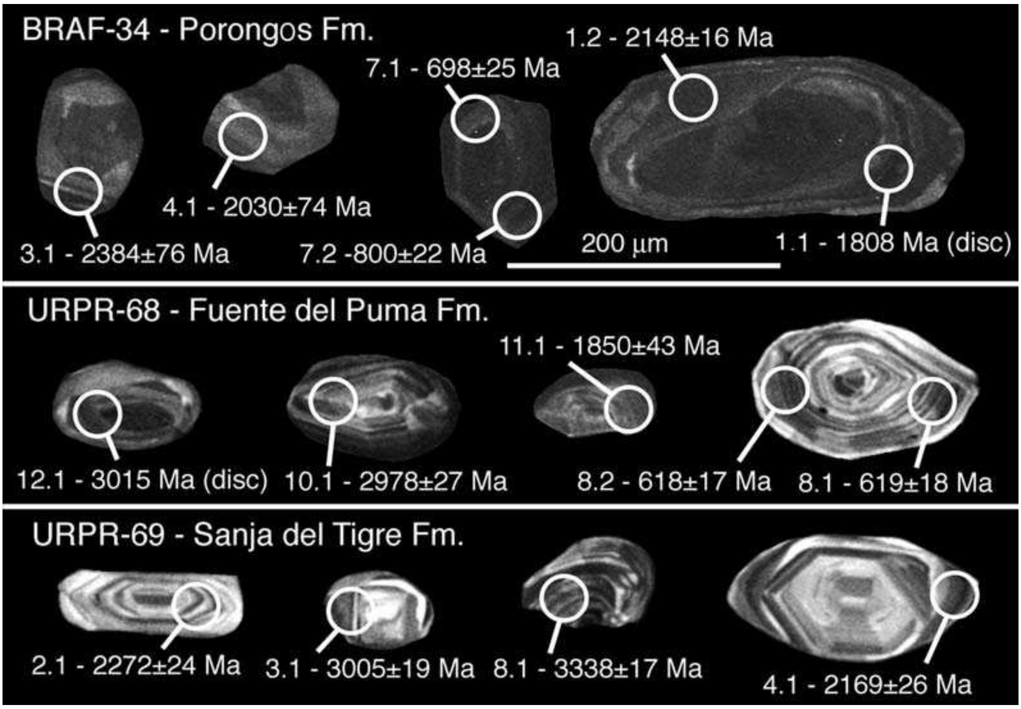

Fig. 6. Cathodo-luminescence images of Dom Feliciano Belt zircon grains.

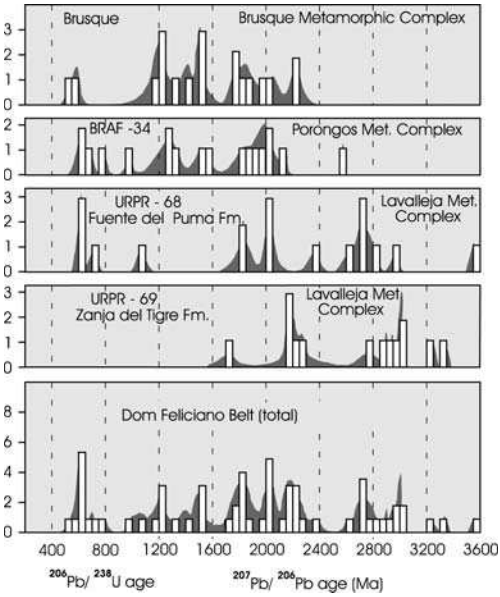

Fig. 7. Histogram of SHRIMP U–Pb and Pb–Pb ages for the Dom Feliciano Belt detrital zircons. Note some detrital zircons with ages around 1.2 Ga. Most of Archaean ages were obtained from samples of the Lavalleja units in Uruguay.

ages are concentrated in the western and youngest units of the Gariep Basin, notably in the Marmora terrane, and could have been derived from the 600 ± 10 Ma Florianópolis–Pelotas batholith (Phillip 1998; Sial *et al.* 1999; Silva *et al.* 1999, 2005; Basei *et al.* 2000).

For the Nosib Group of the Damara Belt, two grains have ages of *c.* 1.0 Ga, there is a main group at *c.* 1.2 Ga, and only two Palaeoproterozoic (1.8–1.9 Ga) grains were detected. Even though this small number of analyses allows only preliminary interpretations, it is noted that no 0.80 Ga zircon ages were found; detrital zircons of this age represent the Gariep Belt, where they correspond to the Richterveld Suite further south. Ages of the Damara Belt units are summarized in Figure 9 and representative CL images for the Nosib Group are displayed in Figure 10.

Age values similar to those presented in this paper have also been noted in other localities in western and southwestern Africa. Mesoproterozoic ages were obtained for detrital zircons from sandstones of the Damara Belt (sample NK 91, Mulden Group) in the northwestern region of Namibia, with detrital zircon populations indicating two main source areas of *c.* 2.0–1.75 Ga and 1.4–1.0 Ga. Metamorphic overgrowth dated at 572 ± 4 Ma was identified on

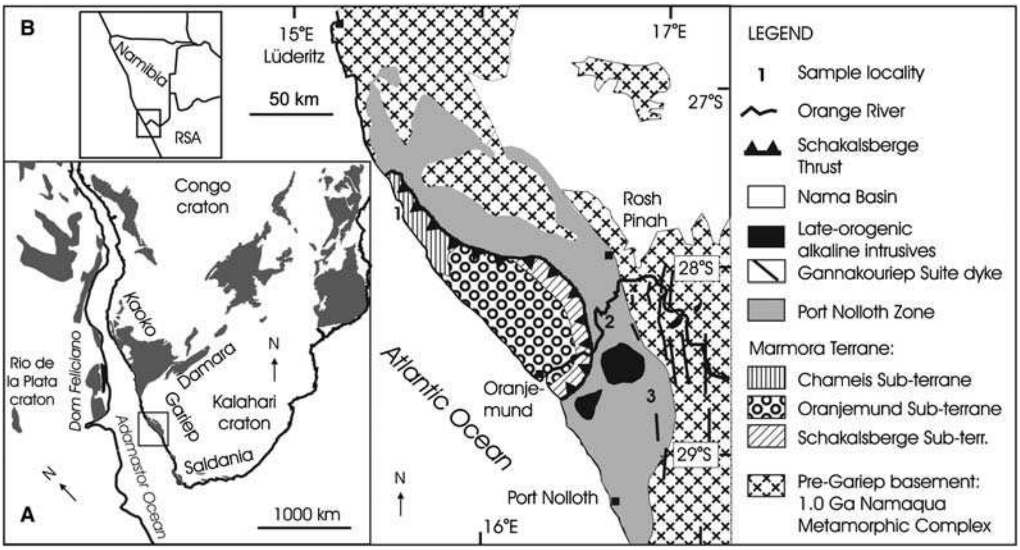

Fig. 8. Geological sketch of the Gariep Belt (after Frimmel *et al.* 2002).

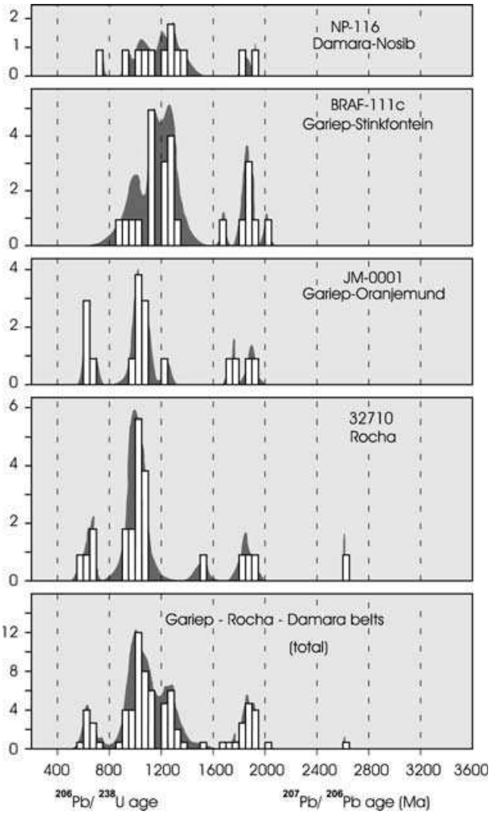

Fig. 9. Integrated histogram of the radiometric ages for detrital zircons from the Gariep and Damara belts.

zircon from the same sample (Goscombe *et al.* 2005). Further north, in the West Congo Belt source areas between 0.8 and 1.2 Ga have been identified for detrital zircons of the Sansikwa, Shiloango and Inkisi subgroups (Frimmel *et al.* 2006). The Inkisi (uppermost), in contrast to the lower groups, shows a predominantly 0.7–0.6 Ga Neoproterozoic detrital zircon population.

No Archaean zircon grains were found in any of the African samples studied, and most grains are <2.0 Ga. This strongly suggests that the basement of the major cratons to the east, such as Kalahari and Congo, were not source areas for the sediments that filled the Damara and Gariep basins. The source for these basins was their own basement, best represented by 1.0 and 1.2 Ga high-grade metamorphic rocks and granites of the Namaqua Metamorphic Complex. Interpretations of the Gariep Basin architecture suggest that the Namaqua complex constituted elevated terrains (Frimmel *et al.* 2002), and thus could be the main source area for the Gariep Basin sediments. At the same time the 'Namaqua Mountains' acted as a barrier for zircons originating in the eastern cratons.

Detrital zircons of 0.9–1.2 Ga are lacking in the southern Ribeira Belt and are rare in the Dom Feliciano Belt but dominate in the African belts. This suggests an African source for such zircons (Fig. 11). On the other hand, in the Central Ribeira Belt segment (Trouw *et al.* 2000; Heilbron *et al.* 2003), located *c.* 700 km NE of the study region in Rio de Janeiro and Minas Gerais states, detrital zircons with ages in the 2.0–2.2 Ga and

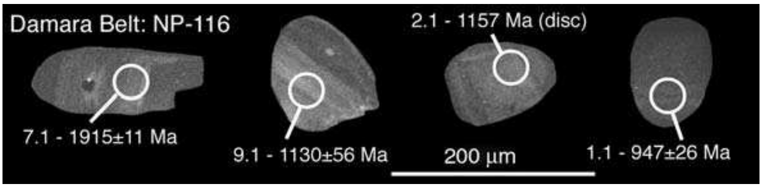

Fig. 10. Cathodo-luminescence images of the Damara Belt zircon grains.

1.0–1.4 Ga intervals are common (Machado & Gauthier 1996; Söllner & Trouw 1997; Valeriano *et al.* 2004; Valladares *et al.* 2004, 2005). Although some of these authors suggest that the possible Mesoproterozoic zircon sources are in the São Francisco Craton, we suggest here the possibility of an African source. Consequently, it is also questioned whether there is a direct correlation between the metasedimentary units that compose the Central Ribeira Belt domain with the occurrences in the south discussed in this paper. In the Búzios region (in the northeast of Rio de Janeiro State), detrital zircons with the same 2.0–2.2 Ga and 1.0–1.4 Ga ages are found in the high-grade metamorphic rocks of the Palmital metasedimentary cover of Palaeoproterozoic gneissic basement (Schmitt *et al.* 2003, 2004). An African source might also be explored for these zircons.

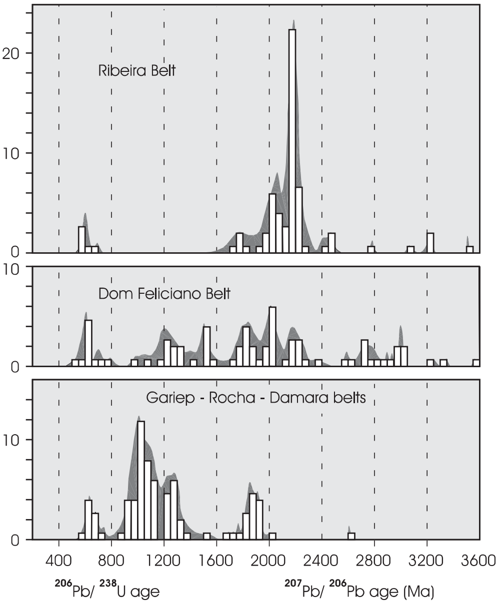

Fig. 11. Integrated histogram comparing the patterns of detrital zircon ages for the Ribeira, Dom Feliciano and Gariep/Damara belts. An eastward increase of age values in the 1.4–1.0 Ga interval is due to African source areas.

Nd model ages Nd (T_{DM}) and zircon provenance patterns

Nd isotopes are considered good indicators of average crustal ages. Regionally uniform Nd isotope signatures can reflect a common geological history and on a broad scale usually allow the identification of distinct crustal domains (Cordani *et al.* 2000).

In the histogram of Figure 12, available Nd (T_{DM}) ages are shown for a roughly west–east transect across the units observed on both sides of the Atlantic Ocean. The histogram shows that there is a conspicuous decrease in model ages eastwards; with the Damara Belt displaying the youngest values. This difference is more striking when some discrepant ages, resulting from problematic analyses (anomalous Sm–Nd ratios, etc.) are eliminated, or when the influence of the basement on the lower units of the metasedimentary pile is taken into account (as exemplified by the Damara Belt). There is a concentration of model ages around 2.0 Ga for the Supracrustal Schist Belt of the Dom Feliciano Belt, whereas for the Eastern Granite Belt the

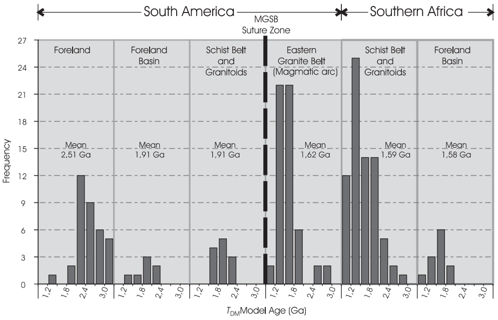

Fig. 12. Pattern of Nd model ages (T_{DM}) for the main geological units that constitute the terrains of southeastern South America and southwestern Africa. The Major Gercino–Sierra Ballena Suture Zone separates both groups of ages. Data sources: Guj (1970), Basei (1985), McDermott (1986), Mantovani *et al.* (1987), May (1990), McDermott & Hawkesworth (1990), Basei *et al.* (1998, 1999, 2000, 2001), Jung *et al.* (1998), Möller *et al.* (1998), Phillip (1998), Cordani & Sato (1999), Silva *et al.* (1999, 2000) and Harara (2001).

average is between 1.3 and 1.6 Ga. For the Damara Belt (mainly its granitoids), the youngest values are 1.1 Ga, but the average is also in the 1.3–1.6 Ga interval. Mesoproterozoic model ages predominate for rocks of the western portion of the Damara Belt (the region between Walvis Bay, Karibib, and the Huab river) with Palmental-type calc-alkaline granitoids, intraplate syenites and granites showing model ages of 1.1–1.5 Ga (McDermott 1986). A very similar pattern was found for the metaluminous A-type granitoids of the Damara central region (Jung *et al.* 1998). Metasedimentary rocks in parts of the Damara (notably Rössing and Kuiseb formations) and Nama (mainly Kuibis and Schwarzrand formations) have Nd model ages similar to those obtained for the Eastern Granite Belt, suggesting that this was an important source area. This corroborates an evolutionary model (Basei *et al.* 2005) that places the Gariep units in a back-arc basin environment and, consequently, the Nama Group on the hinterland side.

This similarity, which may represent an affinity of the source areas for the Eastern Granite Belt and the African portion, can be explained by the participation of similar sources in the generation of these materials. Therefore, the isotopic differences between the Eastern Granite Belt and those further west, even for those of similar crystallization ages, strengthen suggestions that the Major Gercino–Sierra Ballena lineament (Fig. 3) should be viewed as a Neoproterozoic suture (Basei *et al.* 2000, 2005). An important gravimetric anomaly along the lineament also supports this interpretation (Hallinan & Mantovani 1993).

Tectonic model

Several models for tectonic correlation across the southern Atlantic Ocean were proposed by Porada (1979, 1989), Torquato & Cordani (1981), Soares *et al.* (2000), Campos Neto (2000), Basei *et al.* (2000, 2005), Cordani *et al.* 2003, Frimmel & Folling (2004), Schmitt *et al.* (2003, 2004), Valeriano *et al.* (2004) and Silva *et al.* (2005), with the later ones proposed within the framework of West Gondwana assembly. Figure 13 shows hypothetical NW–SE sections from the Ribeira to the Gariep Belt. Figure 13a is a representation at *c.* 0.61 Ga, when subduction zones were active with magmatic arcs being generated. These arcs are now represented by the Cunhaporanga and Três Córregos batholiths in the Ribeira Belt, the Piên batholith between the Curitiba and Luís Alves terranes, and the Florianópolis–Pelotas–Aiguá batholith between the Dom Feliciano and Gariep/Damara belts on the African side. Figure 13b represents the tectonic situation at *c.* 0.53 Ga, just after the collisions during Gondwana assembly, and displays the location of the suture zones.

The westward collision between the Florianópolis–Pelotas–Aiguá batholiths and the Dom Feliciano supracrustal belt occurred at *c.* 0.60 Ga. However, on the African side, only at *c.* 545 Ma did eastward-directed nappes and regional metamorphism affect the supracrustal units (Frimmel & Frank 1998). This event was expressed on the South American side by reactivation of 0.60 Ga structures, and deformation in the foreland basins (Itajaí, Camaquã and Arroio del Soldado). The deformation of African foreland basins (e.g.

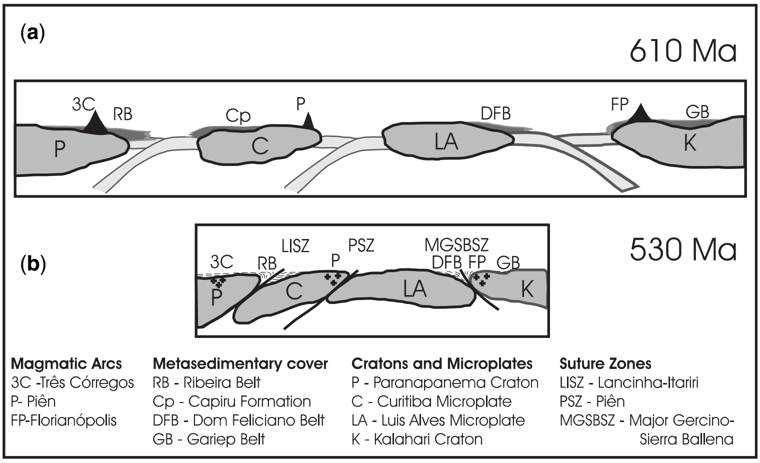

Fig. 13. Simplified tectonic model emphasizing the main geological units that were juxtaposed during collisions associated with the formation of Gondwana. Remnants of the oceanic crust are known only in the Piên region: (**a**) situation before collisions; (**b**) after collisions.

Nama) also started at around 0.54 Ga (older units) but continued through the Cambrian.

The terranes east of the Major Gercino–Sierra Ballena lineament (proposed suture) are interpreted as remnants of African terranes that were juxtaposed during the formation of West Gondwana. After opening of the South Atlantic, only small parts of these belts were preserved in South America.

Testing the tectonic model

As proposed by Basei *et al.* (2000, 2005) and discussed in this work, the Gariep–Rocha–Damara and Dom Feliciano belts represent units deposited at the opposite margins of the ocean that separated the African and South American pre-Gondwana palaeocontinents. In this tectonic context, the Dom Feliciano Belt represents a passive margin associated with the Luis Alves microplate and the Rio de la Plata Craton. However, deposition of the Gariep Belt metavolcano-sedimentary units took place in a back-arc basin related to the Florianópolis–Pelotas–Aiguá magmatic arc that was generated from the eastward subduction of oceanic crust under the Kalahari Craton (Fig. 13a).

If the proposed model is correct, all the units east of the Major Gercino–Sierra Ballena lineament would have African sources. This model, initially based on the pattern of Nd age distribution, is now supported by detrital zircon age data. This was further tested by dating zircons from a Queçaba Formation metasediment. The Quecaba Formation represents one of the few metasedimentary units that overlie the Florianópolis Batholith, east of the Major Gercino–Sierra Ballena lineament. It is in tectonic contact with the batholith rocks, and is composed of phyllites, quartzites and greywackes (Zanini *et al.* 1997). They are foliated and carry greenschist-facies assemblages. According to the model proposed above (Fig. 13), the Queçaba Formation should have an 'African' signature like the Gariep Belt, and should be different from the Dom Feliciano Belt.

As shown in Figure 14, an 'African' signature is evident for the Queçaba Formation, with Mesoproterozoic zircons of mostly *c.* 1.2 Ga. A second age peak falls in the 1.7–1.9 Ga interval, attributed to the Richtersveld terrane that represents pre-Namaqua basement granitoids. It is interesting to note that despite the proximity of the Florianópolis Batholith granitoids, the source area of Queçaba Formation sediments is not related to the erosion of these Neoproterozoic rocks, because no zircons in this age interval have been detected. Additionally, Nd model ages for these metasediments cluster around 1.6 Ga, differing from Palaeoproterozoic values around 2.0 Ga typical of the Brusque Metamorphic Complex to the west of the Major Gercino–Sierra Ballena lineament. The age pattern for the Queçaba Formation metasediment detrital zircons supports the model of Basei *et al.* (2000, 2005).

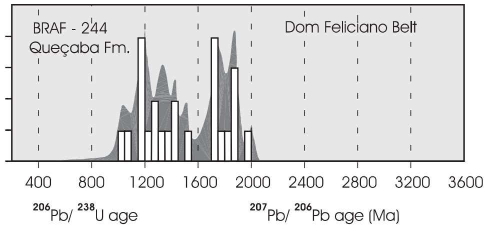

Fig. 14. Histogram of SHRIMP U–Pb ages for the Queçaba Formation detrital zircons. Note the main peak around 1.2 Ga and the lack of Neoproterozoic ages.

Conclusions

(1) The pattern of zircon U–Pb ages for the basement terrains throughout southeastern Brazil and Uruguay is marked by Archaean and Palaeoproterozoic values with noted lack of late Mesoproterozoic grains. Detrital ages of 0.9–1.2 Ga are considered an 'African' signature, typified by the Gariep and Damara belts and inherited from their basement of Namaqua Metamorphic Complex. This signature was only found in the Rocha Group in extreme southeastern Uruguay.

(2) The 'African' signature of the detrital zircon grains of the Rocha Group makes sense if this group is understood as a continuation of the Gariep Belt, now isolated in South America by the opening of the modern Atlantic.

(3) The Dom Feliciano Belt is regarded as a Neoproterozoic passive margin basin developed on the 'Brazilian side' of an ocean that originally separated it from the Gariep Belt (Fig. 13).

(4) The southern units of the Ribeira Belt are derived exclusively from South American sources, such as the Paranapanema Craton.

(5) For the Dom Feliciano Belt, detrital zircon grains from its three segments indicate Neoproterozoic ages, assigning deposition of these supracrustal units to the Brasiliano cycle.

(6) It is possible that the Zanja del Tigre Formation, rather than belonging to the Lavalleja Belt, constitutes part of the basement of this belt, with probable sedimentation in the Mesoproterozoic. This interpretation is based on the detrital zircon ages obtained in this study, on its higher metamorphic grade and its association with granitoids with ages of *c.* 1750 Ma.

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