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# Provenance of the Ediacaran-Early Palaeozoic Arroyo Del Soldado Group (Uruguay) and the Nama Group (Namibia): Geodynamic Implications for the SW-Gondwana amalgamation.

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**Resumen:** *Procedencia del grupo Arroyo del Soldado (Uruguay) y el grupo Nama (Namibia): Implicaciones geodinámicas para el SW de la amalgamación del Gondwana.*- Los resultados de petrografía, análisis de minerales pesados y geoquímica del Grupo Nama se caracterizan por una composición similar a la corteza continental superior reciclada con fuentes principalmente metamórficas-graníticas y con un componente máfico subordinado. Paleocorrientes de areniscas que contienen spinelos cromíferos pertenecientes a la Cuenca Nama indican una fuente localizada en el cinturón Damara. Edades U-Pb de circones detríticos del Grupo Nama muestran que los picos más importantes son Neoproterozoicos y Mesoproterozoicos y sugieren una proveniencia de los cinturones Damara-Gariep y sus basamentos. Paleocorrientes desde el oeste en los sedimentos molasicos de la Cuenca Nama y edades U-Pb en circones detríticos correspondientes al Neoproterozoico-Cambriano (76%) indican probablemente una fuente proveniente de una raíz de arco volcánico de composición félsica exhumada luego de la edad indicada por el circón mas joven que es de 531 ±9 Ma. La petrografía y los resultados geoquímicos del Grupo Arroyo del Soldado indican una composición comparable a la corteza continental superior reciclada y se caracteriza por una diversidad de fuentes granítico-gnéisica y rocas maficas metamórficas. En promedio isótopos de Nd presentan valores negativos de $\varepsilon_{Nd}$ y edades $T_{DM}$ similares a las encontradas en el Gondwana. Edades U-Pb en circones detríticos indican fuentes principalmente Palaeoproterozoicas (1.7-2.0-2.2 Ga) y subordinadamente Arqueanas (2.5-2.9-3.5 Ga). La escasez de circones detríticos Meso-Neoproterozoicos y paleocorrientes hacia el este indican que el Grupo Arroyo del Soldado fue alimentado con detritos del cratón del Río de la Plata favoreciendo un ambiente geotectónico de margen pasivo para su depositación. Deformación del Grupo Arroyo del Soldado ca. 530 Ma ocurrió luego de colisión tangencial con un terreno de afinidad Africana. Finalmente la evolución paleogeografica basada en el análisis de proveniencia de la Cuenca Nama y la Cuenca del Grupo Arroyo del Soldado sugiere que la amalgamación del los cratones Kalahari/Congo con el cratón del Río de la Plata y el terreno Cuchilla Dionisio Pelotas (Arachania) ocurrió probablemente por acrecíon tangencial relacionado a un componente de esfuerzos N-S en un periodo durante 530 a 495 Ma.

**Abstract:** *Provenance of the Ediacaran-early paleozoic Arroyo del Soladado group (Uruguay) and the Nama group (Namibia): Geodynamic implications for the SW-Gondwana amalgamation.*- The petrographic, heavy mineral analyses and geochemical results from the Nama Group indicate a recycled upper crust composition characterized mainly by metamorphic and granitic and minor mafic rocks sources. Paleocurrent analyses of the chromian spinel bearing sandstones of the Nama Basin point to a volcanic island arc source located in the Damara Belt. Detrital zircon dating of the Nama Group display major peaks of Neoproterozoic and Mesoproterozoic ages suggesting a provenance from the Damara/Gariep Belts and their basements. Paleocurrents from the west and the dominance of Neoproterozoic-Cambrian detrital U-Pb zircon ages (76%) in the "Molasse" stage of the foreland evolution probably indicate exhumation of the felsic volcanic arc root which probably occurred after the time indicated by the younger zircon dated at 531 ±9 Ma. The petrographic and geochemical results from the Arroyo del Soldado Group indicate a recycled upper crust composition characterized by source diversity composed of granite-gneissic and mafic-metamorphic rocks. On average, Nd isotopes account for negative $\varepsilon_{Nd}$ values and $T_{DM}$ ages in a range of variation found elsewhere within SW Gondwana. Detrital U-Pb zircon dating indicate sources dominated by Paleoproterozoic (1.7-2.0-2.2 Ga) and subordinate Archaean ages (2.5-2.9-3.5 Ga). The scarcity of Mesoproterozoic and Neoproterozoic zircons and paleocurrent directions towards the east indicate that the Arroyo del Soldado Group was fed by detritus from the Río de la Plata Craton favouring a passive margin tectonic setting for their deposition. Deformation of the Arroyo del Soldado Group took place ca. 530 Ma, after strike-slip collision

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with an African affinity terrane. Finally, based on the paleogeographic evaluation, the provenance of Nama foreland basin and the passive margin deposit of the Arroyo del Soldado basin suggest that continent-continent collision of the Kalahari/Congo Cratons with the Río de la Plata Craton and the Cuchilla Dionisio Pelotas Terrane (Arachania) most likely occurred due to strike-slip accretion related to a component of N–S shortening in the period between 530 and 495 Ma.

**Palabras clave:** Ediacarano. Grupo Nama. Grupo Arroyo del Soldado. Procedencia. SW Gondwana.

**Key words:** Ediacaran, Nama Group. Arroyo del Soldado Group. Provenance. SW Gondwana.

## Introduction

The amalgamation of SW Gondwana in the Neoproterozoic–early Paleozoic resulted from a series of tectonic events related to the subduction of oceanic lithosphere, collision of continental blocks, mantle plume activity and accretion of exotic terranes, within the Pan-African–Brasiliano Belts (e.g. Dalla Salda, 1982; Germs, 1983, 1995; Unrug, 1996; Cordani *et al.*, 2000; Basei *et al.*, 2000; 2005; Bossi and Gaucher, 2004; Gray *et al.*, 2006) (*Figure 1A-B*). Recent geochronological studies in the Pan-African and Brasiliano Belts indicate that the assembly of SW Gondwana was only completed by the end Cambrian and/or early Ordovician but their tectonic evolution remains controversial (e.g. Babinski *et al.*, 1996; Seth *et al.*, 1998; Jung *et al.*, 2000; Schmitt *et al.*, 2004; Saalmann *et al.*, 2005a-b, 2006; Gray *et al.*, 2006; Borba *et al.*, 2006; Goscombe *et al.*, 2007; Rapela *et al.*, 2007; Gaucher *et al.*, 2008a, 2009; Blanco *et al.*, 2009a-b).

The Ediacaran to Cambrian Arroyo del Soldado Group (ASG) is a passive margin sedimentary sequence, preserved in a key area of the Río de la Plata Craton (RP) and was probably deposited before strike-slip collision with a crustal fragment with African affinity named the Cuchilla Dionisio-Pelotas Terrane (Bossi and Gaucher, 2004; Gaucher *et al.*, 2008a) (*Figure 2 A-C*), part of the newly defined Arachania (Gaucher *et al.*, 2009a-d). In Namibia, the Neoproterozoic-early Palaeozoic Nama Group sediments can be interpreted as deposited in a peripheral foreland basin related to the Damara Belt and as an intracratonic or retroarc foreland basin to the Gariep Belt (Germs, 1995; Basei *et al.*, 2005) (*Figure*s *3-4-5*). The Damara Orogen (Kaoko, Gariep and Damara Belts) itself is understood to represent a collisional triple junction (e.g. Prave, 1996; Trompette, 1997; Frimmel and Frank, 1998) but the geological evolution with the Río de la Plata Craton and the tectonic-setting of their sedimentary basins is a question of debate.

The purpose of this study is to analyses the main provenance characteristics with emphasis in the single grain U-Pb zircon data of the Nama Group and compare with the Arroyo del Soldado Group and present a paleogeographic model for the amalgamation of SW Gondwana (Blanco, 2008).

### EARLY RIFTING OF THE KALAHARI AND CONGO CRATONS AND SUBDUCTION IN THE RPC

Rifting at 746 ±2 Ma (Hoffman *et al.*, 1996) and deposition of extensive passive margin platform successions characterize the opening of the Khomas Sea, which started with the separation of the Kalahari and Congo/Angola Cratons and the generation of oceanic crust. A minimum age for rifting in the Gariep Basin can be constrained from U-Pb zircon age of 771 ±6 Ma from rift-related rhyolites (Frimmel *et al.*, 2001) which formed from the opening of a back-arc type basin in the Kalahari Craton (Basei *et al.*, 2005). Extensive siliciclastic deposits are represented by the upper part of the Port Nolloth Group on the western side of the Kalahari Craton (*Figure 2A*; Frimmel and Frank, 1998).

Contemporaneously with the rifting event within the Kalahari Craton, the volcanic São Gabriel Arc was likely accreted to the RPC at ca. 700-750 Ma and was part of an active margin (*Figure 1B*; Babinski *et al.*, 1996; Saalmann *et al.*, 2005).

## RPC Rifting and Provenance of the Post-Rift Arroyo del Soldado Group

An extensional or rift event and deposition of the bimodal volcano-sedimentary Las Ventanas Formation between 615 to 580 Ma (Blanco and Gaucher, 2005; Gaucher *et al.*, 2008b), is accompanied by the emplacement of the Nico Pérez Dyke Swarm at 581 ±14

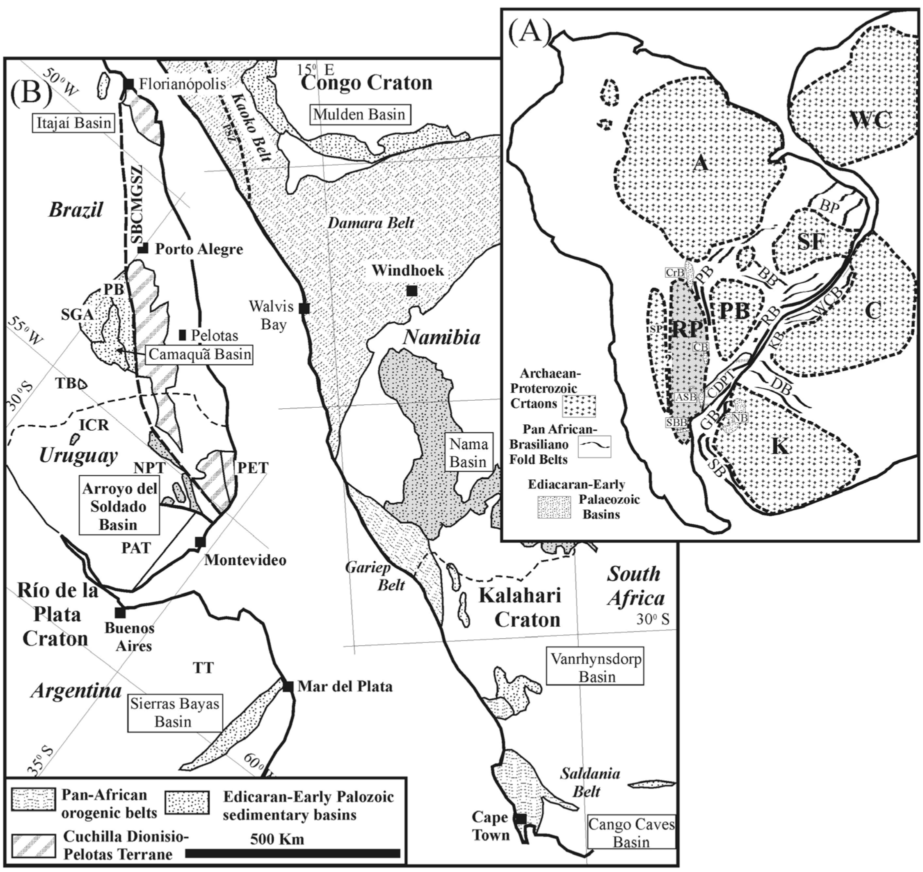


**Figure 1.** Pan-African/Brasiliano orogenic belts and Ediacaran–early Palaeozoic basins in southwestern Gondwana (modified after Gresse *et al.*, 1996; Trompette, 1997; Gaucher *et al.*, 2005).

(A) GB: Gariep Belt, SB: Saldania Belt, DB: Damara Belt, NB: Nama Basin, ASB: Arroyo del Soldado Basin, SBB: Sierras Bayas Basin, CB: Camaquã Basin, SP: Sierras Pampeanas, CrB: Corumbá Basin, RB: Ribeira Belt, KB: Kaoko Belt, WCB: West Congo Belt, PB: Paraguay Belt, BB: Brasilia Belt, BP: Borborema Province, CDPT: Cuchilla Dionisio-Pelotas Terrane.

(B) TT: Tandilia Terrane, PA: Piedra Alta Terrane, NP: Nico Pérez Terrane, PET: Punta del Este Terrane, RB: Rivera Block. ICR: Isla Cristalina de Rivera, SGA: São Gabriel Arc, PB: Porongos Belt, SBCMGSZ: Sierra Ballena-Canguçú-Major Gercino Shear Zone.

Ma (Rivalenti *et al.*, 1995). Intraplate magmatism at around 590 ±2 Ma in the southern Nico Pérez Terrane (Mallmann *et al.*, 2007) could be related to the above mentioned dyke swarm. This extensional event probably resulted in the opening of the Brazilides Ocean and separated the RPC from Arachania (Gaucher *et al.*, 2009) to form a large rifted margin along the eastern border of the RPC (Gaucher *et al.*, 2008b). Deposition of the Yerbal and Polanco Formations (lower Arroyo del Soldado Group, ~560 Ma; *Figure 6A*) took place along the eastern border of the Río de la Plata Craton, wherefrom the main input of detrital material occurred (Blanco *et al.*, 2009a).

Recently Oyhantçabal *et al.* (2009) obtained a U-Pb SHRIMP age of 573 ±11 Ma for ehudral zircon grains of a volcaniclastic rock of Las Ventanas Formation in agreement to the age assigned by Blanco and Gaucher (2005) and Gaucher *et al.* (2008b) based on the finds of microfossils and their biostratigraphycal analysis which was previously assumed as Ordovician by Sanchez-Bettucci *et al.* (2003). Oyhantçabal et al 2009, argue in favour on a evolution from back-arc to a foreland basin for the tectonic setting of the Las Ventanas Formation and ASG respectively and the subduction to the west beneath the RPC (retroarc foreland basin). In this hypothetical scenario the most important detrital zircon peaks of the ASG Group must show a Neoproterozoic signature derived from the magmatic arc as happened with Nama Group (Blanco 2008; Blanco *et al.*, 2009b) or others foreland basins elsewhere. The inferred mollase sedimentation attending the hypothesis supported by Sanchez-Betucci *et al.* (2001) implies an uplift and exposure of the hypothetical source area represented by the Aiguá Batholith and their basement (Dom Feliciano Belt) feeding the Arroyo del Soldado Basin (see below). Typically the development of a mollase sequences in a foreland setting shows the evolution from marine to continental sedimentation and not the opposite as in the case of the Las Ventanas Formation and the overlying ASG. Notwithstanding that the geotectonic setting proposed by Sanchez-Bettucci *et al.* (2001, 2003) is based in the geochemistry analyses of metamorphosed volcanic rocks assigned to Lavalleja Group, which is of uncertain stratigraphic position, showing Neoproterozoic, Mesoproterozoic and Archaean ages (Mallman *et al.*, 2007; Bossi and Cingolani, 2009).

Different hypotheses have been put forward to explain this extensional event, such as slab-break off after the main magmatic event that occurred in the Brasiliano Orogeny around 650-600 Ma (Chemale Jr., 2000), or to plume activity as proposed by Gaucher *et al.* (2009a). The passive margin characteristics of the Yerbal Formation are suggested based on petrography, whole-rock geochemistry, Sm-Nd isotope geochemistry and detrital zircon dating. A provenance from the west, from the basement rocks of the RPC Craton is indicated for the Yerbal Formation as demonstrated by palaeocurrents and the dominant Palaeoproterozoic zircon population (2.0-2.1 Ga) but also a minor Mesoproterozoic population is recorded (Gaucher *et al.*, 2008; Blanco *et al.*, 2009a). Close to the western border of the RPC the Pie de Palo Complex in the Western Sierras Pampeanas (*Figure 1A*) is exposed and is one probable source of Mesoproterozoic zircons for the Yerbal Formation, and may have been autochthonous to the proto-Andean margin of Gondwana (Ramos, 2000; Galindo *et al.*, 2004; Mulcahy *et al.*, 2007). Geochemical proxies (McLennan *et al.*, 1993) used to analyze the Yerbal Formation characterized a basin where recycling played the most important role (e.g. Eu/Eu*~0.6, Th/Sc >1, Th/U >5) which is petrographically supported by the absence of volcanogenic detritus. Arc-related geochemical signatures were only detected in the northernmost part of the basin, which were probably a consequence of sediment supply derived from the São Gabriel Arc (ICR, *Figure 1B*). In the rest of the basin, negative $\varepsilon_{Nd}$ (average -12) and Palaeoproterozoic $T_{DM}$ ages were observed. Up section,

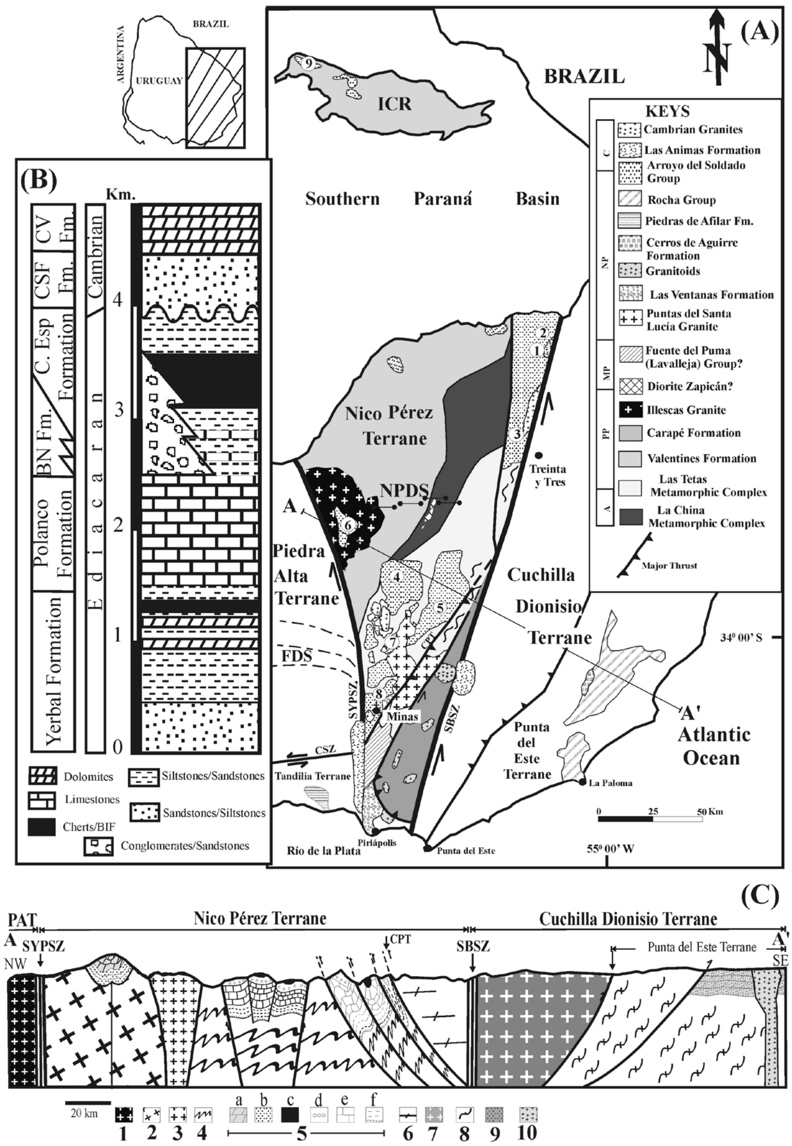


**Figure 2.** (A) Neoproterozoic-Cambrian (volcano) sedimentary successions in Uruguay, pre-Ediacaran basement rock of the ASG and some important intrusive granites. Numbers indicates the sample location. ICR: Isla Cristalina de Rivera, FDS: Florida Dyke Swarm (1.8 Ga), A: Archaean, PP: Palaeoproterozoic, M: Mesoproterozoic, NP: Neoproterozoic, C: Cambrian, NPDS: Nico Pérez Dyke Swarm (0.6 Ga). Modified after Bossi *et al.* (2005), Gaucher (2000) and Hartmann *et al.* (2001). Numbers represent the sampled localities.
(B) Synthetic stratigraphic column of the ASG, after Gaucher (2000). BN Fm.: Barriga Negra Formation, C. Esp: Cerro Espuelitas Formation, CSF: Cerros San Francisco Formation, C.V. Fm.: Cerro Victoria Formation.
(C) Cross section A-A', modified after Gaucher (2000). 1: Piedra Alta Terrane (2.0-2.2 Ga) 2: Illescas Rapakivi Granite (1.75 Ga), 3: Valentines Formation (2.1-2.6 Ga), 4: Archaean Basement (2.6-3.4 Ga), 5: Arroyo del Soldado Group, a: Cerro Victoria Formation, b: Cerros San Francisco Formation, c: Cerro Espuelitas Formation, d: Barriga Negra Formation, e: Polanco Formation, f: Yerbal Formation, 6: Carapé Group (ca. 1.7 Ga), and Neoproterozoic Granites, 7: Aiguá Batholith (~0.6 Ga), 8: High grade gneisses (2.0-0.8 and 1.0 Ga), 9: Rocha Group, 10: post-tectonic granites (~550 Ma). SYPSZ: Sarandí del Yí Shear Zone, CPT: Cerro Partido Thrust, SBSZ: Sierra Ballena Shear Zone, CSZ: Colonia Shear Zone.

deposition of the Polanco Formation, a continuous carbonate plataform (900 m in thickness) indicates the development of a stable shelf that becomes deeper to the east (Gaucher *et al.*, 2003). Conglomerates of the the Barriga Negra Formation transitionally overlie the Polanco Formation. The Barriga Negra Formation was deposited after 566 Ma based on the youngest detrital zircon analyzed. Due to the immature characteristics of the Barriga Negra Formation sediments, the sources can be traced mainly to the Archaean, Palaeoproterozoic and Neoproterozoic rocks in the Nico Pérez Terrane. The obtained Neoproterozoic zircon population shows ages between 566 ±8 and 631 ±12 Ma (29%), which are probably related to magmatism and associated anorogenic granitoids in the above mentioned Nico Pérez Terrane (Blanco and Gaucher, 2005; Gaucher *et al.*, 2009d). Climatic or tectonic (rifting?) causes could explain the deposition of conglomerates filling palaeo-valleys as a consequence of sea-level oscillations (Gaucher, 2000). Deposition of the partly coarse-grained sediments of the Barriga Negra Formation indicate strong palaeorelief and a sea level fall as a consequence of a late Ediacaran non-global ice age characterized by a negative $\delta^{13}$ C excursion (Gaucher *et al.*, 2005a; Gaucher *et al.*, 2008c; Gaucher and Poiré, 2009a). The overlying Cerro Espuelitas Formation comprises thick marine chemical and fine clastic deposits (>2000 m in thickness). The large amount of chemical sediments indicates that the clastic input to the shelf was low due to a sea level highstand (Gaucher, 2000). The unit is geochemically comparable with unrecycled Upper Continental Crust, shows negative $\varepsilon_{Nd\,(t)}$ values with Nd model ages of 2.1 Ga and was probably derived from Palaeoproterozoic rocks of the RPC (Hartman *et al.*, 2001), suggesting that it was deposited in a passive margin setting. In the RPC during the lowermost Cambrian, the super-mature quartz-arenites of the Cerros San Francisco Formation and dolostones of the Cerro Victoria Formation were deposited on a shallow marine platform (Gaucher *et al.*, 2007). Detrital zircon populations and the $T_{DM}$ ages of the Cerros San Francisco Formation (Gaucher *et al.*, 2008a, Blanco *et al.*, 2009a) can be traced to the Archaean and Palaeoproterozoic basement rocks of the RPC (Hartman *et al.*, 2001). In the Tandilia Tarrane, the Sierras Bayas Group (*Figure 1B*) is correlative with the Nama Group and the ASG on basis of their litho-, chemo- and biostratigraphy and were deposited in a passive margin tectonic setting (Dalla Salda *et al.*, 2006; Gaucher *et al.*, 2005b, 2008a; Gaucher and Poiré, 2009b; Bossi and Cingolani, 2009). Thus, the palaeogeographic model recently proposed by Rapela *et al.* (2007) showing the RPC attached to the Kalahari Craton between 550 and 540 Ma is in contradiction with the data presented in this work.

## CUCHILLA DIONISIO-PELOTAS TERRANE AND THE KALAHARI CRATON CONNECTION

The Gariep Belt is correlative with the eastern side of the Cuchilla Dionisio-Pelotas Terrane in Uruguay (*Figures 1B and 3B*; Punta del Este Terrane), both of which share a Namaqua-age basement and are part of Arachania (Preciozzi *et al.*, 1999; Bossi and Gaucher, 2004; Basei *et al.*, 2005; Gaucher *et al.*, 2009). The Rocha Group in the Punta del Este Terrane (*Figures 1 and 2A-C*) and the Oranjemund Group in the Marmora Terrane (*Figures 2 and 7B*) are correlative based on very similar detrital zircon age population patterns (Basei *et al.*, 2005). Both units were deposited between 600 and 550 Ma and are characterized by a common provenance mostly derived from the Namaqua-age basement and the Neoproterozoic arc granites (*Figure 7B*; Basei *et al.*, 2005). The youngest ages obtained from detrital zircons in both groups (~600 Ma) indicate derivation from Arachania (Basei *et al.*, 2005; Gaucher *et al.*, 2009). Syn-collisional to late orogenic granite emplacement was very intense and rather continuous in the interval between 680-550 Ma in Arachania (Preciozzi *et al.*, 1999; Gaucher

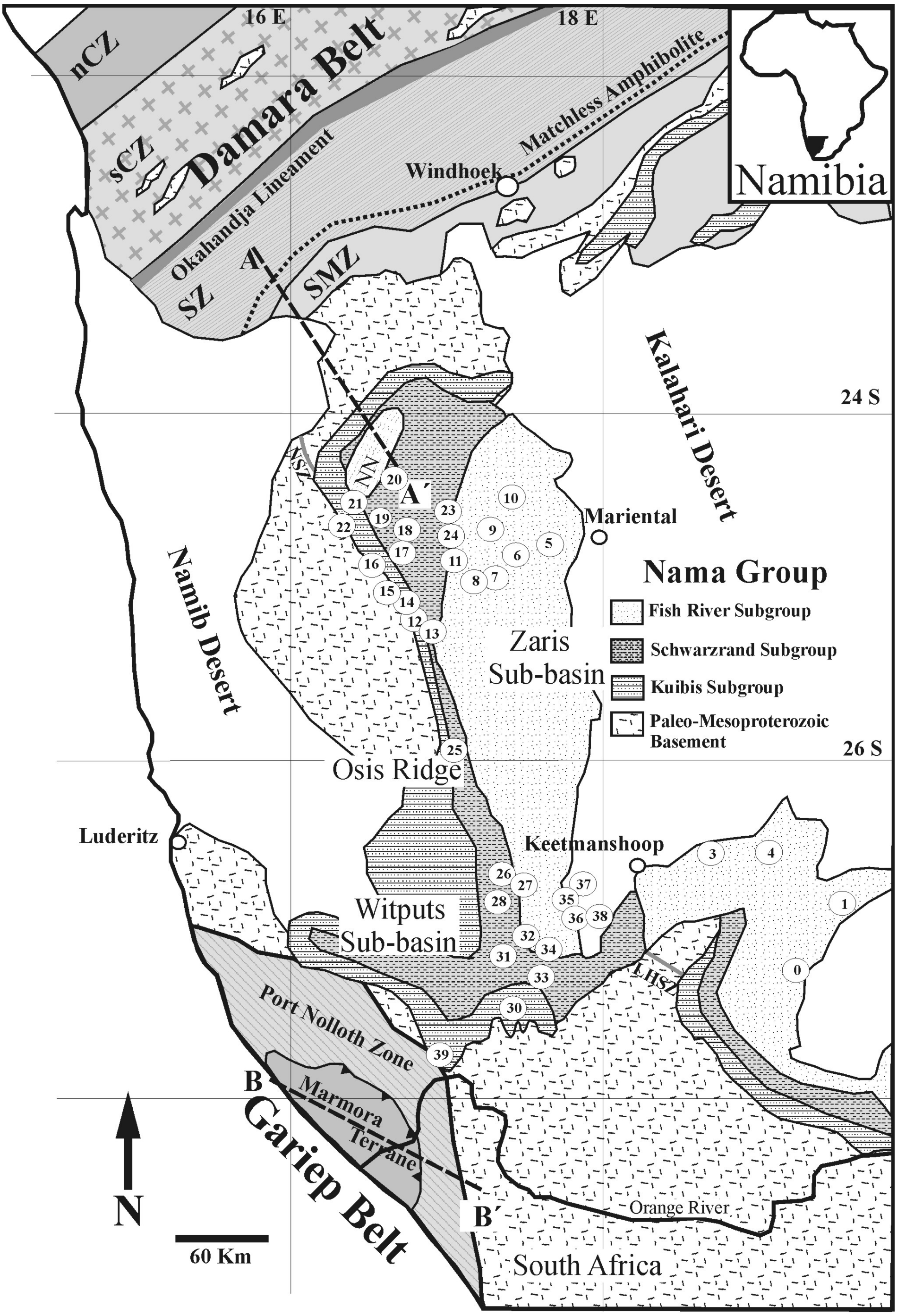


**Figure 3.** Regional map showing the location of the Nama Group, the Damara and Gariep Belts and the working area. Modified after Saylor *et al.* (1995). CZ: Central Zone, SZ: Southern Zone, SMZ: Southern Marginal Zone, RBI: Rehobot Basement Inlier, NSZ: Nam Shear Zone. Cross sections A-A' and B-B' are shown in figure 4. Circled-numbers represent the different localities selected for sampling.

*et al.*, 2009). Two main metamorphic events recorded in the Chameis Group of the Marmora Terrane occurred at ca. 575 Ma and 545 Ma (Frimmel and Frank, 1998). Extrusive magmatism is represented in the Cuchilla Dionisio Terrane by pyroclastic rocks and dacites of the Cerros Aguirres Formation that yielded a U-Pb SHRIMP age of 572 ±8 Ma (Hartmann *et al.*, 2002; *Figure* 2A). It is clear that the Cuchilla Dionisio-Pelotas Terrane is an allochtonous block and probably accreted to the RPC ca. 530 Ma, after the deposition of the ASG (Bossi and Gaucher, 2004). In the RPC the Lower Cambrian, passive margin deposits of the Cerros San Francisco Formation contain no Mesoproterozoic zircons (of a total of 135 analyzed grains; Gaucher *et al.*, 2008a, Blanco *et al.*, 2009a). There is a conspicuous absence of Neoproterozoic zircons derived from the magmatic arc represented by the batholiths in the Cuchilla Dionisio Pelotas Terrane, developed between 550 and 650 Ma (*Figures 6B-C*). In the *Figure 8* note the similar age distribution between the Rocha Formation and Nama Group (see below) compared with the ASG.

## THE PROVENANCE OF THE NAMA FORELAND BASIN

At ca. 550 Ma the deposition the lower Nama Group began (Grotzinger *et al.*, 1995). The Kuibis Subgroup (*Figure* 5) unconformably overlies various stratigraphic units of the Neoproterozoic Porth Nolloth Zone in the Gariep Belt and its Mesoproterozoic Namaqua-Natal basement (Germs, 1972a-b-c, 1974, 1995; Germs and Gresse, 1991; Frimmel and Frank, 1998). During early Nama depositional times (Kuibis and lower Schwarzrand Subgroups) the foreland basin consisted of three sub-basins separated by the northern Osis (*Figure* 3) and southern Kamieskroon Arches, which probably represented forebulges (Germs and Gresse, 1991). The lower Nama Group received material predominantly from the eastern Kalahari Craton although palaeocurrents had changed during deposition of the northern Nudaus Formation, when sediment transport took place from a north-northwestern source in the Damara Belt (*Figures 3, 4A and 5*; Germs, 1983). However, during late Nama depositional times (upper Fish River Subgroup) these arches lost their importance and the detrital material was shed from northern sources into one major foreland basin (Germs and Gresse, 1991). The sediments of the Stockdale and Breckhorn Formations of the lower Fish River Subgroup were supplied from the west, and according to Germs (1983) most probably from the Gariep Belt (*Figure* 4B).

The petrography of the Kuibis Subgroup sandstones shows a dominance of polycyclic subfeldsarenites with a craton interior provenance, and agrees with the palaeocurrent analyses made by Germs (1983) which imply a source mainly derived from the Kalahari Craton. The geochemistry of the Kuibis Subgroup mudrocks (Th/Sc~0.6, Th/U~2.9 and Eu/Eu*~0.7) show a volcanic arc signature, pointing to a provenance from a Mesoproterozoic mafic basement in the case of the Witputs Sub-basin, which was recently documented in the Karas Mountains by Evans *et al.* (2007). Contrasting, in the northern Zaris sub-basin, syn-tectonic volcanic activity from the Gariep-Damara Belts could be the reason for an input of fine-grained volcanic material (Germs, pers. comm.).

Reid *et al.* (1991) dated a metamorphic amphibolite dyke emplaced during transpressional tectonism in the Gariep Belt, yielding a $^{40}Ar$-$^{39}Ar$ age of 545 ±2 Ma and interpreted as recording the continent-continent collision event. According to Frimmel and Frank (1998), peak of metamorphism attained lower amphibolite facies conditions in the Port Nolloth Zone, which was due to emplacement of the Marmora Terrane on top of the former. Amphibolites from the Marmora Terrane yield hornblende $^{40}Ar$-$^{39}Ar$ plateau ages between 547 ±4 and 543 ±6 Ma, and therefore record the age of continent-continent collision between the Río de la Plata and Kalahari Cratons (Frimmel and Frank, 1998). However, the geochemical and petrographical data, as well as zircon dating presented for Nama Group strata below the Nomtsas Formation (Blanco, 2008; Blanco *et al.*, 2009b; *Figure 5*) could not detect any collisional event to the west of the basin. Indicators such as Zr concentrations >1000 ppm (UCC= 190 ppm; after McLennan *et al.*, 2006), Th/Sc ratios up to 4.33 and Zr/Sc ratios > 30, maximum 445, are indicative of extreme reworking. Detrital zircon ages for the Urusis Formation from the Witputs and Zaris sub-basins indicate a derivation from the Mesoproterozoic basement and the Neoproterozoic orogenic belts. Compressive tectonic processes towards the west of the Nama Basin probably produced thin-skinned tectonics reflecting small-scale movements rather than large-scale regional geological events.

The deposition of the upper Nama Group started with the Nomtsas Formation (539 Ma; Grotzinger *et al.*, 1995), representing the first incursion of coarse fluvial deposits into the basin (Germs, 1983; Germs and Gresse, 1991). Regional palaeocurrent directions for the Zaris sub-basin indicate a main derivation from the Damara Belt, suggesting that uplift and erosion were dominated by a continent-continent collision between the Kalahari and Congo Cratons at the time of the Nomtsas Formation deposition (Germs, 1983; 1995). The Niep Member (Nomtsas Formation) shows zircon populations dominated by Neoproterozoic and Mesoproterozoic ages, displaying major peaks at 632, 902, 1057 and 1892 Ma. The input of volcanic material is corroborated by the preserved volcanic lithoclasts, euhedral chromian spinels and pyroxenes with inclusions of chromian spinel with a volcanic arc geochemical signature (Blanco *et al.*, 2009b). This detrital record can explain a slight shift of Th/Sc ratios to values below 1 and slightly higher Eu/Eu* values (between 0.7 and 0.85) compared with

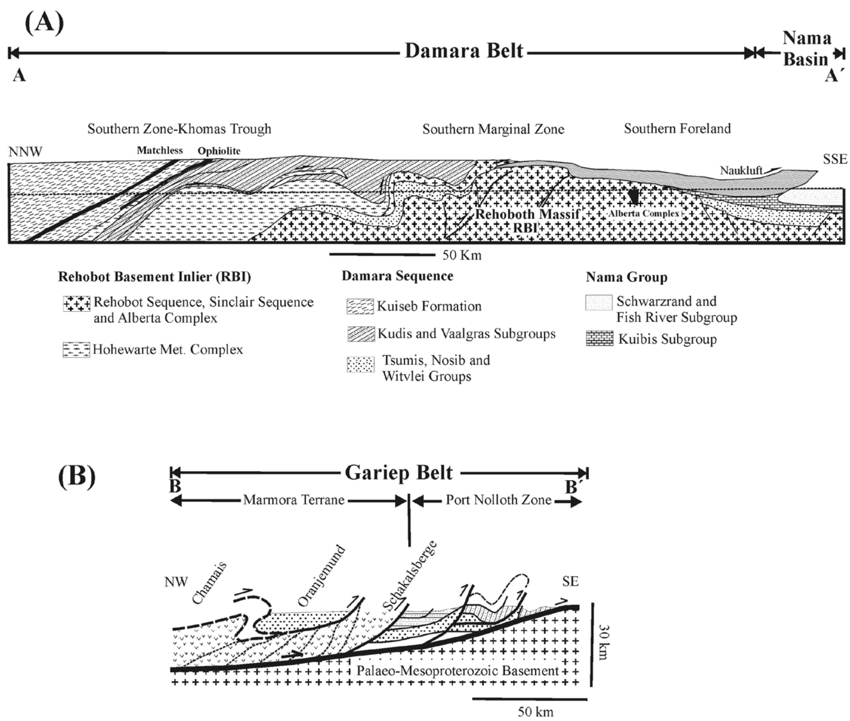


**Figure 4.** (A) Cross section of the southern Damara Belt, modified after Hoffman (1994) and Prave (1996). (B) Crustal architecture of the Gariep Belt modified after Gray *et al.* (2006), Frimmel and Frank (1998). Location of the A-A' and B-B' cross sections are shown in figure 3.

the underlying units (Blanco, 2008). This shift could be explained by an influence of volcanic rocks from the Damara Belt as indicated by the sediment supply from the north (Germs, 1983).

The deposition of the Fish River Subgroup "molasse" sediments in a fluvial to shallow marine environment shows a palaeocurrent pattern derived from the west at the base, and from the north towards the top of the subgroup (Germs, 1983). The subgroup originated from reworked sediments of the Damara Orogen (Hortsmann *et al.*, 1990), and shows extreme recycling based on petrography and geochemistry (Blanco, 2008), the latter characterized by high Th/Sc (~3), low to high Th/U (1.9-7.2) and negative Eu/Eu* values (~0.5). Zircon dating performed in the Wasserfall Member of the lower Fish River Subgroup, clearly indicate a dominance of Lower Cambrian and Neoproterozoic ages (76% of the analyzed zircons with peaks at 546, 591 and 637 Ma), and the sedimentation cannot be older than 531 ±9 Ma. Thus, the Wasserfall Member source probably was derived from the Neoproterozoic granites of the Nico Pérez and Cuchilla Dionisio Terranes and the Cambrian felsic magmatism associated with the latest movements of the Sierra Ballena-Canguçú-Major Gercino Shear

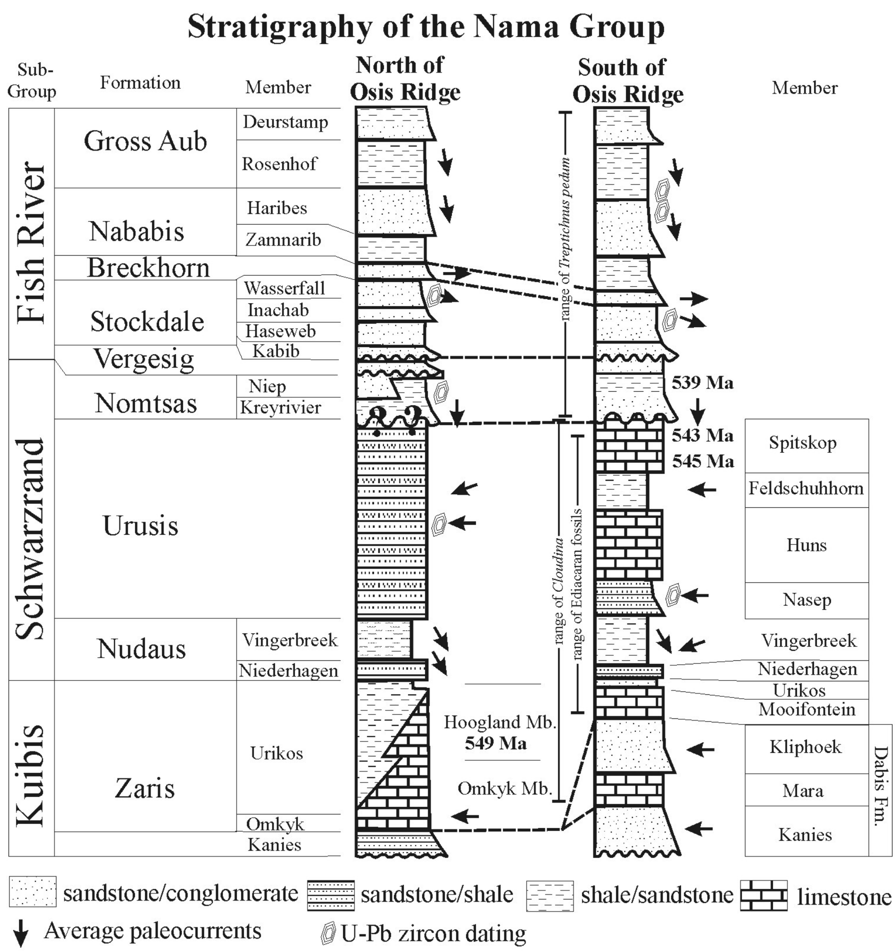


**Figure 5.** Stratigraphic columns from the Zaris sub-basin (north of Osis ridge) and Witputs sub-basin (south of Osis ridge) and their palaeocurrents average of the Nama Group, after Germs (1983). Ages represent tuff layers dated by Grotzinger *et al.* (1995) and palaeontological data after Germs (1972a).

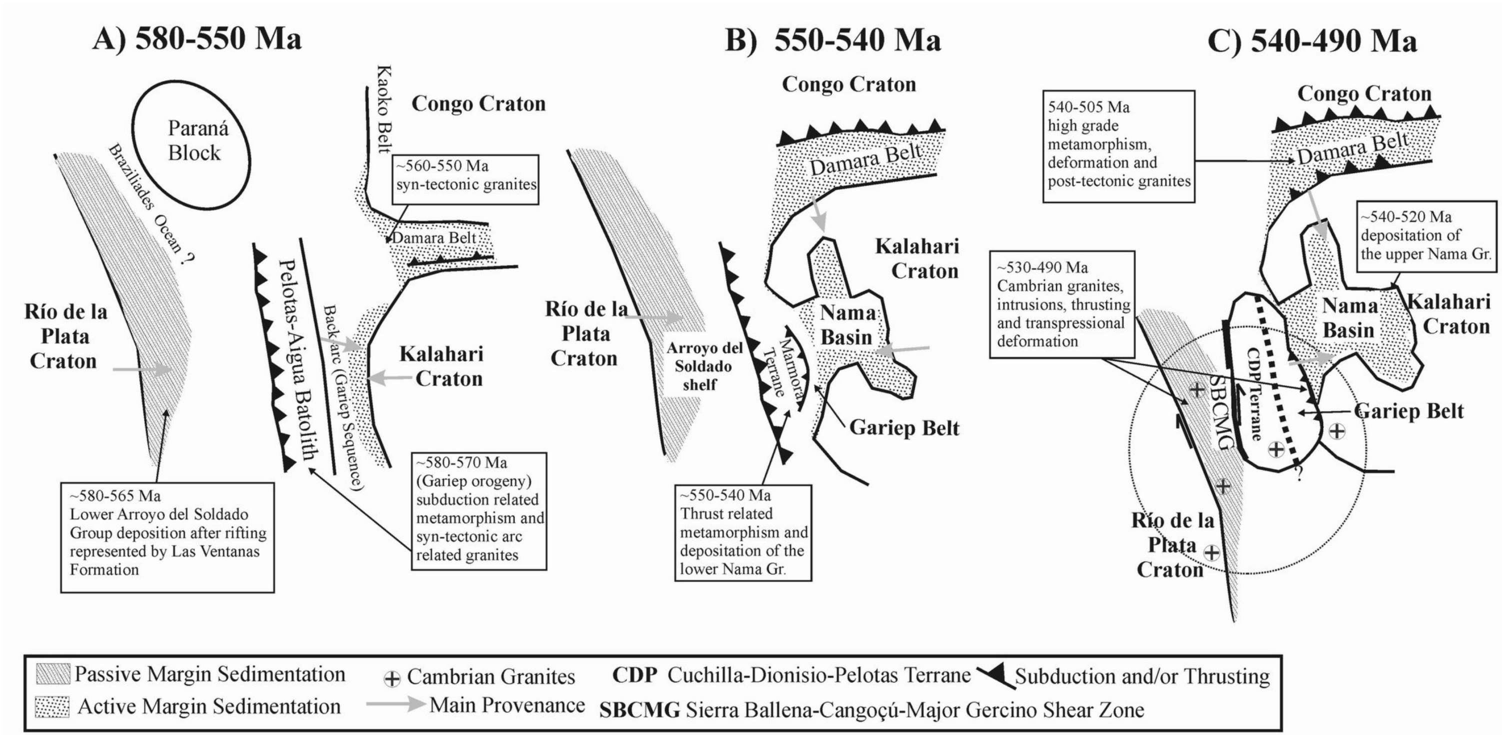


**Figure 6.** Palaeogeographic evolution of SW Gondwana between 580 and 490 Ma. See text for explanation and references.

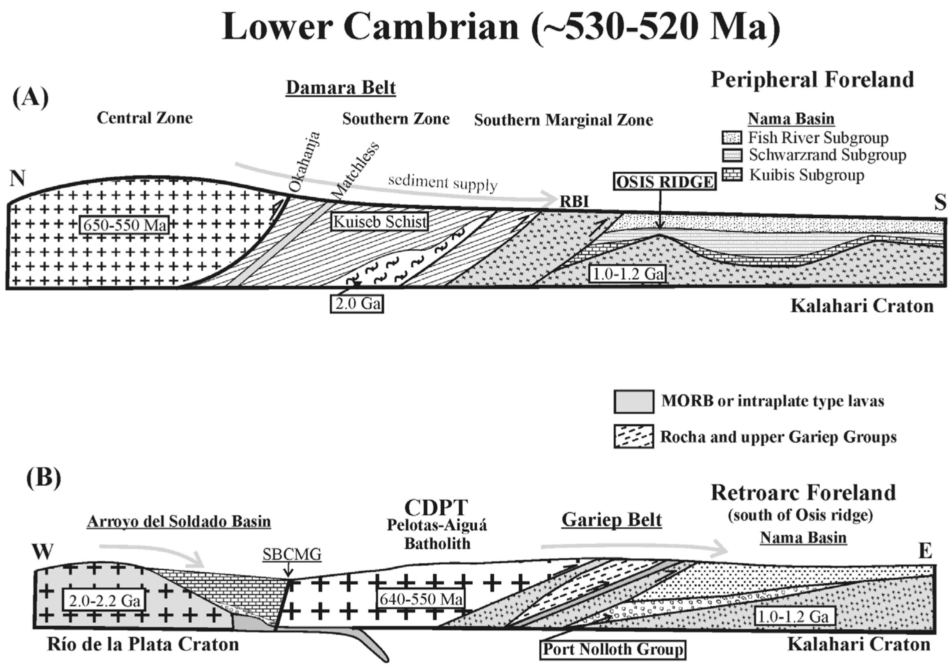


**Figure 7.** (A) Schematic N-S cross section of the Damara Belt showing the main areas of sediment supply for the upper Nama Group. RBI: Rehobot Basement Inlier. (B) Proposed location of the Río de la Plata and Kalahari Cratons at ca. 530 Ma based on provenance data of the Arroyo del Soldado and Nama Basins. CDPT: Cuchilla Dionisio-Pelotas Terrane. SBCMG: Sierra Ballena-Canguçú-Major Gercino Shear Zone.

Zone located in southernmost Brasil and Uruguay. Most of the Neoproterozoic zircon sources could be traced in the Cuchilla Dionisio-Pelotas Terrane (ca.550-650 Ma; Silva *et al.*, 1999) which was the feeder of the Wasserfall Member after the closure of the Rocha-Gariep Basin according to the tectonic model presented by Basei *et al.* (2005). (*Figures 6C and 7B*). Current lines of thinking indicate that the Kaoko and Gariep Belts and their counterpart, the Cuchilla Dionisio-Pelotas Terrane, in South America have been parts of an active margin with subduction beneath the Kalahari and Congo Cratons (Goscombe and Gray, 2007) and is supported by the data presented in this work.

The petrographic and chemical analyses on black sands of the Haribes/Rosenhof Members show the input of euhedral garnet from the Damara Belt and chromian spinels with a MORB signature which was probably derived from the Matchless Amphibolites (Blanco *et al.*, 2006, 2009b), which is supported by palaeocurrents derived directly from the north (Germs, 1983). The overthrusting and exhumation of different metamorphic rocks point to the Damara Belt as the most probable source for the obtained Mesoproterozoic zircon population (*Figure* 3A). The obtained Neoproterozoic zircon peaks (626, 592, 569 and 547 Ma) are probably related to the syn-tectonic granites of the Central Zone in the Damara Belt (*Figures 3A, 6A and 7B*). Granitic plutonism within the Damara Belt is recorded over a period of at least 150 Ma between ~620 and ~470 Ma (e.g. Kröner, 1982; Miller, 1983).

## FINAL BASINS CLOSURE AND AMALGAMATION OF THE KALAHARI AND RÍO DE LA PLATA CRTATONS

In the Damara Belt, the closure of the Khomas Sea is represented by the intrusion of syn-tectonic granites between ca. 650 and 550 Ma and post-tectonic granites at ca. 500 Ma

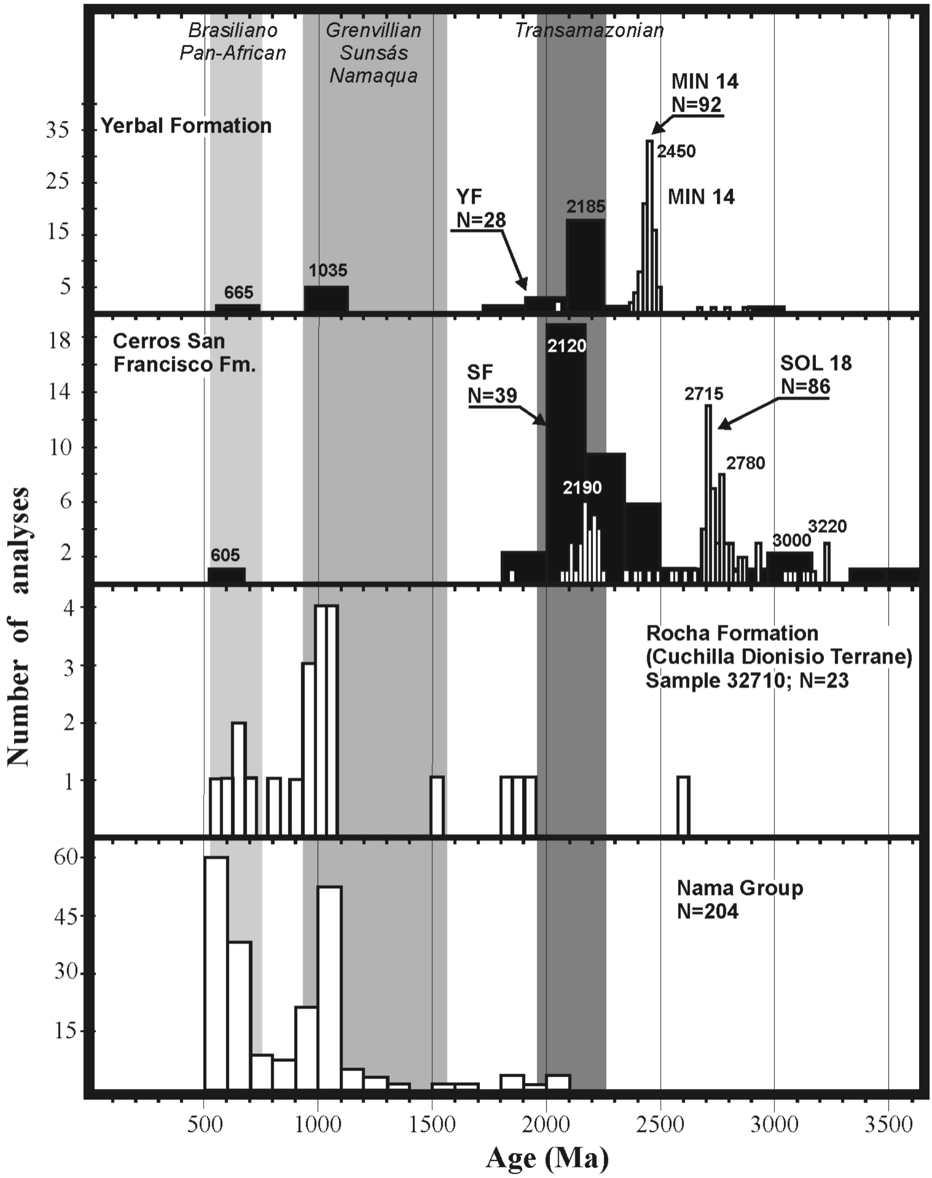


**Figure 8.** Detrital zircon age spectra for the Arroyo del Soldado and Nama groups and Rocha Formation, after Blanco *et al.* (2010). Samples MIN 14 and SOL 18 from Gaucher *et al.* (2008a), SF and YF from Blanco *et al.* (2009a), 32710 from Basei *et al.* (2005) and those of the Nama Group from Blanco (2008). Note the radical difference between the source areas of samples from the ASG (Río de la Plata Craton) and those of the Rocha Formation and Nama Group (Arachania and Kalahari Craton).

(Kröner, 1982; Miller, 1983; Jung, 2000; Johnson *et al.*, 2006). The Cambrian-Ordovician period is characterized by granitic intrusions, thrusting and deformation propagating onto the Kalahari Craton to the south (Damara Belt) and east (Gariep Belt), from ~495 to ~480 Ma (Germs and Gresse, 1991; Gresse and Sheepers, 1993), which probably was contemporaneous with the closure of the southern Adamastor Ocean (Germs, 1995; Frimmel and Frank, 1998; Gray *et al.*, 2006).

Deformation and Cambrian granitic intrusions took place in the ASG at ca. 530 Ma in response to tangential collision between the Nico Pérez and Cuchilla Dionisio-Pelotas Terranes probably as response of the Buzios Orogeny (*Figure* 2C; Bossi and Gaucher, 2004; Gaucher *et al.*, 2009a-b-c; Bossi and Cingolani, 2009). Moreover, Gray *et al.* (2006) suggested thrusting in the Gariep Belt represents a shear zone reactivation due to the continent-continent collision of the Kalahari/Congo Cratons with the RPC. Recently, the Gariep Belt was linked to the external branch of the Kaoko Belt (Coastal Terrane) and the Cuchilla Dionisio-Pelotas Terrane, which has been affected by transpressional deformation related to a component of N–S shortening in the period between 530 and 495 Ma (*Figure* 6C; Gray *et al.*, 2006; Goscombe and Gray, 2007).

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