Regional Geology Reviews

Siegfried Siegesmund
Miguel Angelo Stipp Basei
Pedro Oyhantçabal
Sebastian Oriolo *Editors*

Geology of Southwest Gondwana

Springer

Regional Geology Reviews

The Geology of—series seeks to systematically present the geology of each country, region and continent on Earth. Each book aims to provide the reader with the state-of-the-art understanding of a regions geology with subsequent updated editions appearing every 5 to 10 years and accompanied by an online “must read” reference list, which will be updated each year. The books should form the basis of understanding that students, researchers and professional geologists require when beginning investigations in a particular area and are encouraged to include as much information as possible such as: Maps and Cross-sections, Past and current models, Geophysical investigations, Geochemical Datasets, Economic Geology, Geotourism (Geoparks etc.), Geo-environmental/ecological concerns, etc.

More information about this series at http://www.springer.com/series/8643

Siegfried Siegesmund
Miguel Angelo Stipp Basei
Pedro Oyhantçabal · Sebastian Oriolo
Editors

Geology of Southwest Gondwana

Springer

Editors
Siegfried Siegesmund
GZG—Structural Geology and Geodynamics University of Göttingen
Göttingen
Germany

Miguel Angelo Stipp Basei
Geosciences Institute
University of São Paulo
São Paulo
Brazil

Pedro Oyhantçabal
Departamento de Geodinámica Interna
Universidad de la República
Montevideo
Uruguay

Sebastian Oriolo
GZG—Structural Geology and Geodynamics University of Göttingen
Göttingen
Germany

and

Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires (IGEBA)
CONICET-Universidad de Buenos Aires
Buenos Aires
Argentina

ISSN 2364-6438 ISSN 2364-6446 (electronic)
Regional Geology Reviews
ISBN 978-3-319-68919-7 ISBN 978-3-319-68920-3 (eBook)
https://doi.org/10.1007/978-3-319-68920-3

Library of Congress Control Number: 2017955254

"The cover photo shows the low-grade and folded sediments of the Ediacaran Rocha Formation (Dom Felicano Belt) at the Atlantic coast of Uruguay. These metasediments, based on the detrital zircon ages pattern and geological similarities are considered the counterpart of the Oranjemund Group (Gariep Belt) cropping out in the western borders of Namibia and South Africa. They were split up in the Mesozoic during the south Atlantic Ocean opening". Photo by Mathias Hueck

Printed on acid-free paper

This Springer imprint is published by the registered company Springer International Publishing AG part of Springer Nature
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Why This Book?

Our understanding of the Earth during the Precambrian has changed dramatically during the last decades. Discussions concerning the onset of plate tectonics, the supercontinent cycle and crustal growth processes have also diversified, with deep implications for Precambrian geodynamics. For this reason, this volume presents an updated synthesis of the state of the art of the Precambrian geology of Southwest Gondwana, including the main controversies and discussions concerning the tectonic and geodynamic evolution of this region during the Precambrian. Major tectonometamorphic, magmatic and sedimentary processes and paleogeographic implications during the late Neoproterozoic are evaluated in detail, as this period represents a key step in the Earth's evolution linked to the assembly of Gondwana.

Gondwana, in Retrospect

After publication of the first world atlas, *Theatrum Orbis Terrarum* (Ortelius 1570), the geographer Abraham Ortelius was the first to recognize the match of the South American and African Atlantic margins (Ortelius 1596). Later, these geometrical similarities constituted one of the main pieces of evidence to support plate tectonics (e.g., Wegener 1915; Bullard et al. 1965). However, geological similarities between both continents were first reported in the nineteenth century.

The term 'Gondwana', coined in the geological literature to refer to a plant-bearing series in India and afterwards extended to the Gondwana system (Feistmantel 1876; Medlicott and Blanford 1879), had previously been used in ethnographic works (Craig Robertson pers. comm.). Remarkably, the Austrian geologist Eduard Suess (1831–1914) was the first to establish regional correlations by the end of the nineteenth century, indicating the existence of a 'larger continent' (Suess 1885). This definition, probably the oldest precursor of the supercontinent concept, was stated by Suess as 'Versucht man ähnliche Vergleichungen auf die vereinigte Masse von Asien, Afrika und Europa anzuwenden, so zeigt sich sofort, dass hier verschiedenartige Gebiete zu einem grossen Continente aneinander geschweisst sind […] Wir nennen es Gondwána-Land nach der gemeinsamen alten Gondwána-Flora', and which can be roughly translated to 'if comparisons are made between Asia, Africa and Europe, it is clear that different areas in these regions were juxtaposed as part of a large continent […] We name it Gondwána-Land, after the shared Gondwana flora.'

Already in his first edition of *Die Entstehung der Kontinente und Ozeane*, Alfred Wegener considered South America, Africa, India and Australia as the main parts of Gondwana (Wegener 1915). Key contributions concerning South America and Africa correlations were first presented by Hans Keidel (1914, 1916) and Alexander du Toit (1927, 1928) and constituted one of the main lines of evidence considered by Alfred Wegener to support continental drift theory (Wegener 1929). Keidel described Upper Paleozoic glacial deposits in the Sierras

Australes de Buenos Aires in Argentina and correlated them with comparable deposits in the Cape Fold Belt (Keidel 1914, 1916, 1938). Motivated by Keidel's contributions, du Toit visited South America and provided further correlations across the South Atlantic (du Toit 1927, 1928, 1937).

First attempts to correlate the Precambrian rocks of South America and Africa were also established during the first half of the twentieth century. Based on the work of Brouwer (1921), Wegener (1929) recognized similarities in the 'old granites' of Brazil and southern Africa. On the other hand, du Toit (1927) stated:

> Prominent are the various belts of pre-Devonian strata in the lengthy stretch between the Río de la Plata and Pernambuco, of which some are probably of Ordovician age, while others may be older. They, however, have a general lithological resemblance to the folded Nama succession on the eastern side of the Atlantic, between Cape Town and Lüderitz, and also possess a strike that is more or less parallel to the coast. This likeness is highlighted by the fact that in certain localities the granite by which these belts are flanked are intrusive, just as in the Nama beds between Cape Town and Namaqualand.

These rocks were characterized by 'a general north-northeasterly trend', and du Toit (1927) attributed them both African and South American margins to the 'Brazilian system' defined by Alcide d'Orbigny in Brazil (Beaumont 1844), arguably corresponding to the oldest correlation of Brasiliano–Pan-African belts (Fig. 1).

After these first correlations, similarities in the Precambrian record of South America and Africa were tightened up significantly. Porada (1979) was one of the first to correlate the Damara and Gariep belts of southern Africa with the Ribeira Belt of South America, and to interpret their evolution in terms of continent collision. These correlations were strongly strengthened by the massive explosion in the application of first geochronological methods

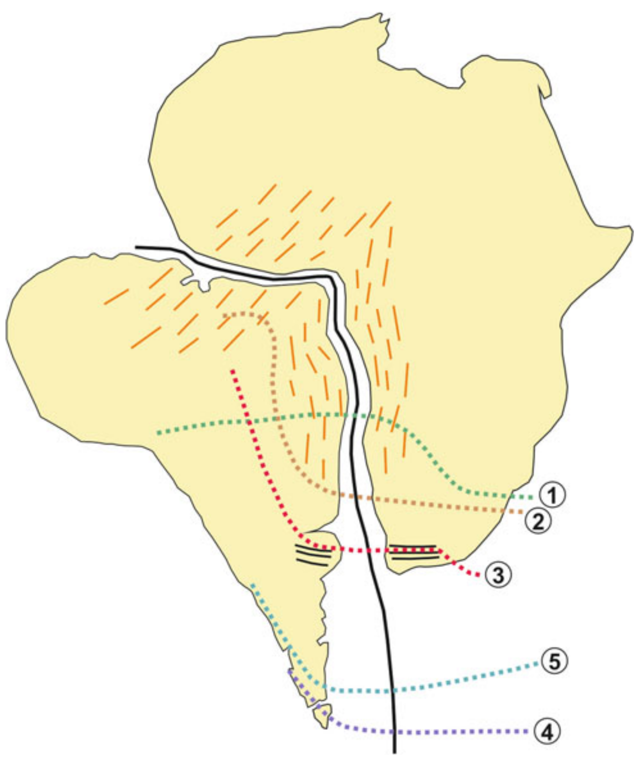

Fig. 1 Schematic reconstruction presented by Wegener (1915), including similarities between the Sierras Australes de Buenos Aires and the Cape Fold Belt (black lines). Handwritten notes made by Alfred Wegener on a copy of Wegener's (1915) work are schematically included in colour (after Wegener 2005): structural trends of basement rocks along both margins of the South Atlantic (orange lines) and northern boundary of marine deposits (1: Lower Cambrian, 2: Lower Devonian, 3: Upper Carboniferous, 4: Upper Triassic, 5: Upper Jurassic)

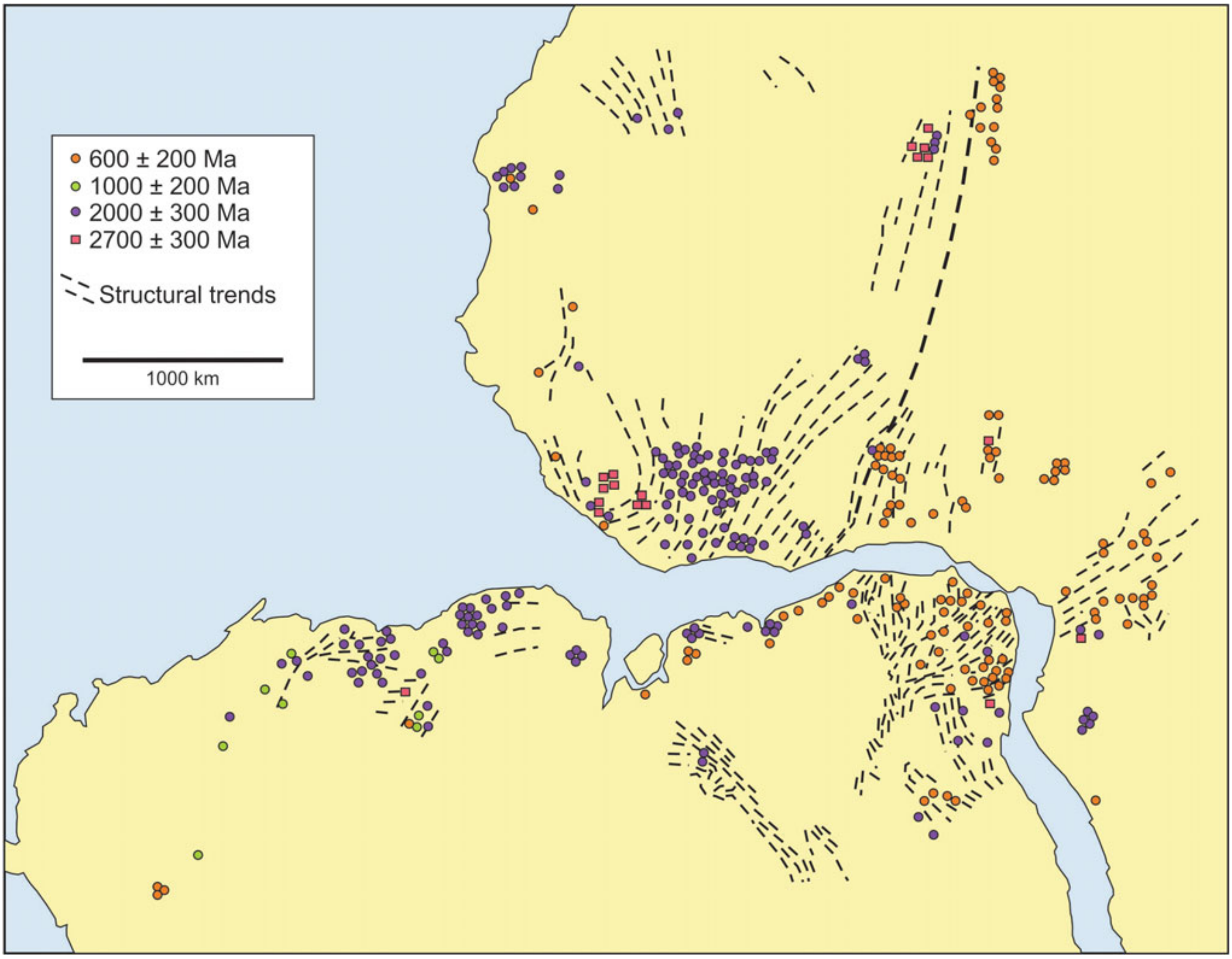

Fig. 2 Geochronological database presented by Hurley et al. (1967) showing similarities in the Precambrian record of South America and Africa (reconstruction after Bullard et al. 1965). Bold dashed line indicates the boundary between domains showing Paleoproterozoic and Neoproterozoic ages

(Torquato and Cordani 1981 and references therein). Correlations of Precambrian rocks of northeastern South America and western Africa, including similarities in structural and metamorphic characteristics, were presented by Pflug (1963), Almeida and Black (1968), and Allard and Hurst (1969). Along with this geological evidence, Hurley et al. (1967) provided a large database of K–Ar and Rb–Sr data, emphasizing similarities in the Paleoproterozoic and Neoproterozoic geological record (Fig. 2). Once again, these correlations constituted a central proof during renewed discussions about the validity of continental drift theory (Hurley 1968).

Likewise, several contributions focused particularly on the southwestern Gondwanan correlations across the Atlantic. Similarities in terms of collisional events and oceanic realms recorded in Brasiliano–Pan-African belts were presented by Almeida et al. (1973), Porada (1979, 1989), Torquato and Cordani (1981), and Hartnady et al. (1985). Based on paleomagnetic data, McWilliams (1981) provided the first apparent polar wander path for Western Gondwana (Fig. 3). The first geochronological data of the Precambrian basement of southern Brazil, Uruguay and Argentina were reported by Hart (1966), Halpern et al. (1970), Halpern and Linares (1970), and Umpierre and Halpern (1971), discussing their possible connection with African counterparts.

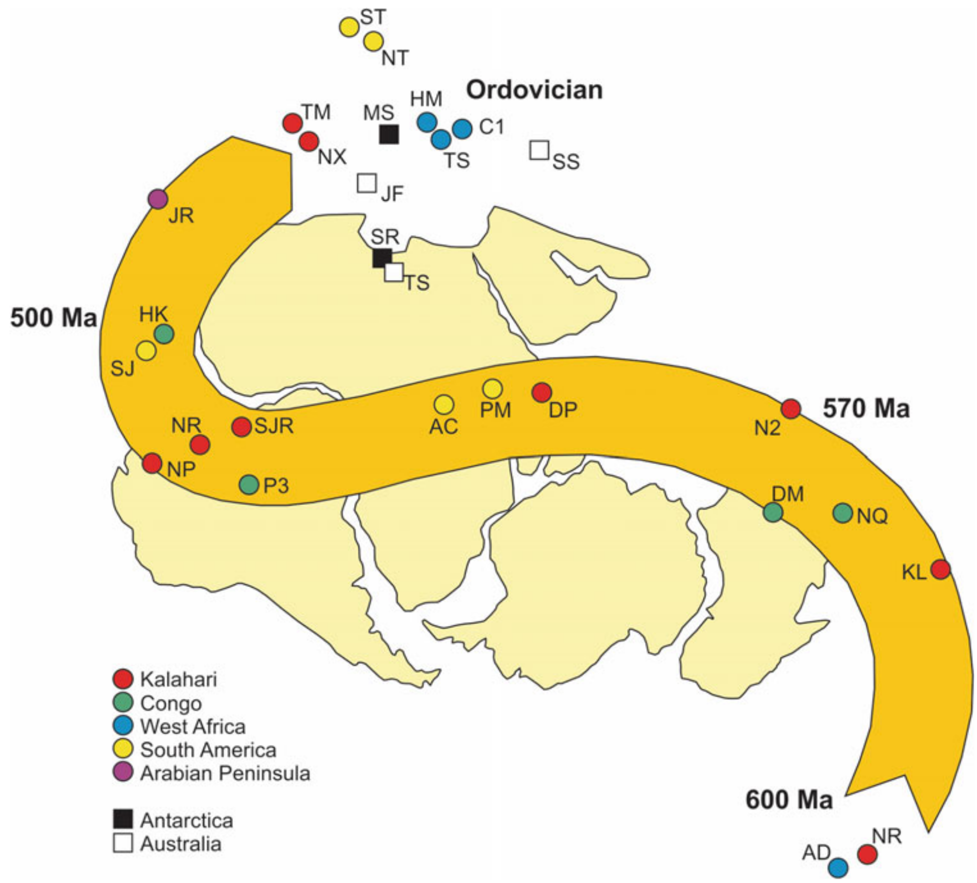

Fig. 3 First apparent polar wander path of Western Gondwana for the late Ediacaran-Ordovician after McWilliams (1981). Equal area projection, reconstruction after Smith and Hallam (1970) with fixed Africa. AD—Adma diorite; NR—Ntonya ring structure; KL—Klipheuvel Formation; NQ—Nosib Group; DM—lower Mulden Group; N2—upper Nama Group; DP—Doornpoort Formation; PM—Purmamarca sediments; AC—Abra de Cajas; P3—Plateau series; SJR—Sijarira Group; NR—Ntonya ring structure; NP—Nama Group—overprint-; SJ—Salta-Jujuy redbeds; HK—Hook intrusives; JR—Jordan redbeds; TM—Table Mountain series; NX—Blaubeker Formation; ST—S. Tilcara; NT—N. Tilcara; HM—Hasi-Mesaud sediments; TS—Tassili sediments; C1—Groupe de la Falaise d'Atar; MS—Mirnyy charnockites; JF—Jinduckin Formation; SR—Sor Rondane intrusives; TS—Tumblagooda sandstone; SS—Stairway sandstone. See McWilliams (1981) for further references

During the last two decades, however, Southwest Gondwana connections were significantly tightened up, particularly as a result of large-scale geological mapping programmes and the massive application of analytical techniques such as SHRIMP and LA-ICP-MS zircon geochronology (e.g. Siegesmund et al. 2011). The aim of this volume is thus to present an up-to-date overview of the Precambrian geology of Southwest Gondwana, emphasizing the role of the main Archean to Paleoproterozoic crustal blocks and the late Neoproterozoic orogenic belts related to the Brasiliano–Pan-African orogeny.

Content

This volume contains 24 chapters written by 54 authors. In Part I, regional overviews based on paleomagnetic and geophysical data are presented, together with a synthesis of the Adamastor Ocean evolution. The evolution of the main crustal blocks—the Río de la Plata, Congo and Kalahari cratons—is summarized in the chapters of Part II. Smaller continental fragments such as the Nico Pérez Terrane, the Luis Alves and Curitiba microplates, and the Angolan Shield are also presented here, whereas the southwestern Brasiliano–Pan-African orogenic belts are described in the chapters in Part III. In Part IV a series of special chapters address key topics regarding the evolution of Southwest Gondwana: ore deposits, BIFs, Brasiliano–Pan-African shear zones, Neoproterozoic glaciations, Late Neoproterozoic-Early Paleozoic sedimentary basins, Ediacaran fauna and the impact crater record.

Rapalini presents an overview of available paleomagnetic data for Western Gondwana blocks and compares them with paleomagnetic constraints of Laurentia and Eastern Gondwana, discussing implications for the Ediacaran-Cambrian paleogeography. Data indicate that, by the early Ediacaran, the Amazonian and West Africa Cratons were probably still attached to Laurentia. On the other hand, the Río de la Plata and Congo-São Francisco cratons were already amalgamated by *c*. 575 Ma, whereas the Arabian-Nubian Shield was probably attached prior to *c*. 570 Ma. Paleomagnetic data from Australia constrain the apparent polar wander path for Eastern Gondwana, pointing to a late Ediacaran-Cambrian assembly with Western Gondwana. Interestingly, the author also outlines the absence of reliable paleomagnetic constraints for the Kalahari Craton.

Corner and Durrheim provide an integrated geophysical and geological framework for the lithospheric structure of southern Africa. A large database comprising geological, borehole, aeromagnetic, gravimetric, magnetotelluric, seismic reflection and refraction, and teleseismic data is carefully evaluated in order to provide insights not only into the Precambrian geology of areas covered by Phanerozoic sequences but also into major terrane boundaries, crustal lineaments and the lower crust-upper mantle structure. As a result, correlations between the main tectonostratigraphic domains and structures of the region are presented, together with implications for the thermal state of the main cratonic domains.

Basei et al. revise the Neoproterozoic history of opening and closure of the Adamastor Ocean between African and South American domains. The authors emphasize in particular the role of magmatic arc petrotectonic assemblages and associated major crustal-scale shear zones. Tonian-Cryogenian crustal extension gave rise to the opening of the Adamastor, succeeded by subduction starting at *c*. 640 Ma. Subduction led to magmatic arc development and, finally, to continental collision of South American and African cratons at *c*. 600 Ma, thus triggering crustal thickening in the Brasiliano–Pan-African belts.

Oyhantçabal et al. review geological, geochronological, isotopic and geophysical data of the Río de la Plata Craton of Argentina and Uruguay. Neoarchean to Paleoproterozoic crustal growth is indicated by Sm-Nd and Lu-Hf data. Widespread granitic-gneissic domains record accretional tectonics at *c*. 2.2–2.1 Ga and were intruded by late- to post-orogenic undeformed granitoids, gabbros and dolerites with a calcalkaline signature at *c*. 2.07 Ma. Subsequent exhumation, cooling and cratonization occurred at *c*. 2050–1800 Ma, succeeded by tholeiitic dyke intrusions at *c*. 1.8 and 1.6 Ga in Uruguay and Argentina, respectively. Despite being involved in the Brasiliano orogeny, the Río de la Plata Craton does not show significant reworking, revealing the presence of a thick and strong lithospheric mantle when it was amalgamated with the rest of Gondwana.

Thiéblemont et al. present an up-to-date geological overview of Precambrian domains in Western Central Africa, including the Congo Craton and adjacent blocks. Archean to Neoproterozoic lithostratigraphical domains are described in detail, along with novel geological maps and a summary of geochronological and Sm-Nd data. As a corollary, the Precambrian tectonic evolution of Western Central Africa is revised, emphasizing the role of crustal growth vs. crustal recycling processes.

Oriolo and Becker summarize the main tectonostratigraphic units of the Kalahari Craton. Geological, geochronological and isotopic data are presented, including a large compilation of U-Pb and Lu-Hf zircon data. The data show episodic crustal growth and accretion of minor crustal blocks during the Archean, also implying reworking of Hadean crustal remnants. The subsequent addition of juvenile Paleoproterozoic crust took place along the western margin of the proto-Kalahari margin, whereas Mesoproterozoic subduction zones were present all around the Archean-Paleoproterozoic proto-Kalahari Craton. The latter gave rise to the accretion of several microcontinents and island arcs along the southern margin during the Namaqua-Natal orogeny. Afterwards, Cryogenian intraplate magmatism was succeeded by the incorporation of the Kalahari Craton into Gondwana during the protracted Pan-African orogeny.

Oyhantçabal et al. integrate geological, geochronological, isotopic and geochemical data of the Nico Pérez Terrane in Brazil and Uruguay in order to constrain its regional extension and Precambrian tectonic evolution. Archean crustal growth was succeeded by major Paleoproterozoic crustal reworking related to multistage magmatism and high-grade metamorphism. The Mesoproterozoic record is restricted to intraplate magmatism and related sedimentary sequences, whereas significant Neoproterozoic crustal reworking during the Brasiliano–Pan-African orogeny is attested by cooling ages, shear zones and granitic intrusions. In addition, the authors emphasize the African origin of the Nico Pérez Terrane, linked to the Congo Craton, and present novel correlations between the southern Brazilian and Uruguayan sectors.

Passarelli et al. revise geological, geochronological, isotopic and geochemical data of the Luis Alves and Curitiba terranes of southern Brazil, establishing the main characteristics of these two Paleoproterozoic crustal blocks. The Luis Alves Craton is composed of a TTG suite, mafic-ultramafic intrusions and scarce paragneisses, whereas the Curitiba terrane comprises migmatites and amphibole-gneissic rocks. On the other hand, Sm-Nd data indicate dominantly Neoarchean to Paleoproterozoic crustal growth for the Luis Alves Craton, and older Meso- to Neoarchean crustal growth for the Curitiba terrane. Both blocks were amalgamated during the Ediacaran along the Pien Suture Zone, triggering significant deformation and migmatization in the Curitiba terrane.

Jelsma et al. summarize new and available geological, geochronological and geochemical data of the Angolan Shield. Three main crustal domains are recognized: the Central Shield Zone in the east, and the Central Eburnean Zone and Lubango Zone in the west. Magmatism recorded in these domains is attributed to continental arcs developed along the active western and southern margins of the Congo Craton, with peak magmatic events at *c*. 2.0–1.96 Ga (Eburnean Event), 1.88–1.83 Ga (Kamanjab-Bangweulu Event) and 1.80–1.77 Ga (Epupa Event).

Phillip et al. evaluate the tectonic evolution of the São Gabriel Terrane in southern Brazil, linked to the evolution of the Charrua Ocean. A large database of geological and isotopic data are presented. Based on these data, the authors provide a three-stage tectonic evolution for the São Gabriel Terrane, which can be divided into the Passinho (*c*. 0.89–0.85 Ga), São Gabriel (*c*. 0.77–0.68 Ga) and Dom Feliciano (*c*. 0.65–0.54 Ma) orogenic events.

Hueck et al. compile geological, geochronological and structural data of the Dom Feliciano Belt in Brazil and Uruguay, discussing models and controversies related to the tectonic evolution of this major transpressional belt. The first phase is recorded in the São Gabriel Terrane, associated with juvenile magmatism and accretional tectonics at *c*. 870–680 Ma. Subsequent high-grade metamorphism, shear zone nucleation and deformation of metavolcanosedimentary units were related to a collision at *c*. 650–600 Ma, succeeded by strike-slip deformation and voluminous post-collisional magmatism at *c*. 600–550 Ma. The final stage corresponds to the development of foreland basins, probably associated with transtension occurring up to the Early Paleozoic.

Goscombe et al. provide a detailed tectonic evolution of the Kaoko-Damara Belt system, evaluating geological, structural, metamorphic and geochronological constraints. The collision of the Río de la Plata and Congo cratons resulted in obduction of the Coastal Terrane over the latter at *c*. 590 Ma and it was succeeded by collision of the Kalahari with the Congo Craton along the Damara Belt at *c*. 555–550 Ma, giving rise to northwest–southeast shortening between *c*. 550 and 530 Ma and consequent transpression with the development of strike-slip shear zones. At *c*. 530–525 Ma, shear zones of the Kaoko Belt underwent transtension, whereas peak metamorphism and deformation associated with north-northwest-south-

southeast crustal shortening is recorded in the Damara Belt, succeeded by northeast-southwest shortening by *c*. 512–508 Ma. A switch to east–west shortening and north–south extension is evident in the Damara Belt at *c*. 508 Ma, probably resulting from far-field effects of tectonic processes along the southern margin of Southwest Gondwana. This north–south extension triggers both decompression melts at *c*. 508–504 Ma and gravitational collapse and extension of the thermally weakened Damara Orogen core at *c*. 505–500 Ma.

Frimmel reviews the tectonostratigraphy of the Gariep Belt and provides an integrated evolution of Neoproterozoic tectonic processes, including interesting insights into contemporaneous sedimentary and paleoclimatic processes. The author indicates the existence of Tonian alkaline magmatism related to crustal thinning and associated late Tonian continental sedimentation that record a progressive transition to shallow marine conditions. At *c*. 750 Ma, the first glaciations of the Gariep Belt are recorded. After a hiatus of *c*. 100 Myr, oceanic magmatism is recorded by the Marmora Terrane, which is interpreted as a late Cryogenian-Ediacaran back-arc basin. Closure of the Marmora Basin took place at *c*. 550–545 Ma, contemporaneously with climatic recovery after the Numees glaciation. Transpressive deformation led to exhumation and erosion, providing detritus for the Nama basin, and was succeeded by post-orogenic Cambrian alkaline magmatism.

Kisters and Belcher present an overview of the stratigraphy, structure, magmatism and tectonic evolution of the Saldania Belt, interpreted as a forearc crustal section that evolved between the late Ediacaran and the Cambrian along the Kalahari Craton margin. The structurally lower Swartland Complex resulted from tectonic underplating during southeast-directed subduction below the Kalahari Craton and is unconformably overlain by low-grade metasediments and minor metavolcanic rocks of the Malmesbury Group that represent the late Neoproterozoic to Cambrian forearc basin fill. Regional deformation of the forearc is characterized by partitioned sinistral transpression related to oblique convergence and was probably associated with slab break-off, thus accounting for voluminous, syn- to late-tectonic magmatism of the Cape Granite Suite.

Schmitt et al. evaluate Cambrian Brasiliano–Pan-African tectonic events in the context of the assembly of Southwest Gondwana, based on the geological database of the new geological map of Gondwana. Not only collisional events but also extensional processes leading to the development of oceanic and back-arc basins are evaluated. Based on this synthesis, the authors establish correlations between Ediacaran-Cambrian orogens of Eastern and Western Gondwana, highlighting potential causal relationships between them.

López de Luchi et al. compile isotopic and geochemical data of the Eastern Sierras Pampeanas and provide a revised tectonic evolution for this key area of the proto-Pacific margin of Gondwana. The authors characterize the metamorphism, magmatism, deformation and tectonic implications of three main events: the Ediacaran to Early Cambrian (580–530 Ma) Pampean, the Late Cambrian-Ordovician (500–460 Ma) Famatinian and the Devonian-Carboniferous (400–350 Ma) Achalian orogenies, which resulted from the complex alternation of subduction-related and collisional processes.

Smith summarizes the main geological, stratigraphic and geochemical characteristics of iron formations of southern Africa. Additionally, he presents an overview of depositional models and the economic significance of these iron formations.

Rosière et al. provide a summary of iron formations of the South American Platform, separating them based on their age and location. Based on the main geological, stratigraphic, mineralogical and geochemical characteristics, implications for the genesis and ore deposit significance are evaluated.

Poiré et al. revise the Neoproterozoic glacial record of South America. They provide stratigraphic, isotopic and geobiological insights into the genesis of these deposits, exposed in Brazil, Paraguay, Bolivia, Uruguay and Argentina. As a corollary, sedimentary successions are divided into "Snowball Earth" and "Phantom Glacial" deposits in order to separate glaciogenic from non-glaciogenic deposits that were, however, influenced by global glaciation processes. Neoproterozoic major climatic and sea level fluctuations are also discussed.

Gaucher reviews the Ediacaran to Early Cambrian fossil record of Southwest Gondwana. Details of the characteristics and occurrence of acritarchs, soft-bodied biota, skeletonized metazoans and protists, and trace fossils are described, discussing the biostratigraphic and paleographic implications.

Zimmermann presents an up-to-date synthesis of provenance data of major Neoproterozoic to Lower Paleozoic sedimentary basins in southern South America and Africa, including key lithostratigraphic features as well as age and provenance constraints. The author provides a thorough discussion of the limitations of the available data and its implications for regional geodynamic and tectonic models. Based on the missing links of the current database, future lines of research are also presented.

Oriolo et al. review geometrical, structural, kinematic, microstructural and geochronological data of crustal-scale shear zones of the Brasiliano–Pan-African belts and discuss the role of these shear zones in the construction of Western Gondwana. Likewise, insights into Phanerozoic shear zone reactivation are also presented, particularly during the Cretaceous opening of the South Atlantic Ocean.

Borg and Gauert describe ore deposits of southern Africa, including some world-class deposits such as the Central African Copperbelt, and evaluate their age, genetic processes and tectonic setting. They emphasize the enormous potential of this region in terms of base (Cu, Pb, Zn, Co, Ni), precious (Au, Ag) and strategic metals (U, W, Sn, Li, Ta, REE). VHMS and SHMS deposits are related to extensional settings, mostly Mesoproterozoic in age, though sediment-hosted stratabound Cu-Ag deposits are also recorded in other volcanosedimentary basins. On the other hand, mantle-derived mafic melts allowed the formation of ore deposits of Cu, Co and Ni, whereas highly fractionated intrusions related to collisional orogens host a range of highly incompatible elements. As a result, the authors emphasize the role of the complex tectonic and geodynamic evolution of Southwest Gondwana, identifying alternating episodes of crustal shortening and extension as one of the main triggers of the wide diversity and availability of ore deposits.

Reimold et al. provide an overview of impact craters of Gondwanan regions. Though the African and South American record is emphasized, Eastern Gondwana craters occurring in Australia and India are also mentioned. A detailed list of impact crater location, size and age, among others, are provided. Finally, the authors emphasize the potential of the region in terms of possibly hidden impact craters, which might be discovered by future studies.

References

Allard GO, Hurst VJ (1969) Brazil-Gabon geologic link supports continental drift. Science 163:528–532

Almeida FFM et al (1973) The Precambrian evolution of the South American cratonic margin, South of Amazonas River. In: Nairn ACM et al (eds) The Ocean Basins and Margins. Plenum, New York, pp 411–446

Beaumont ME (1844) Report on M. Alcide D'Orbigny's memoir, entitled General considerations on the geology of South America. The Edinburgh New Philos J 37:111–131.

Bullard E. et al (1965) The fit of the continents around the Atlantic. Philos T Roy Soc A 258:41–51.

du Toit AL (1927) A Geological Comparison of South America with South Africa. Carnegie Institution of Washington, Washington, 158 p

du Toit AL (1928) Some reflections upon a geological comparison of South Africa with South America. Proc Geol Soc South Africa 19–38.

du Toit AL (1937) Our Wandering Continents. Oliver and Boyd, Edinburgh, 366 p

Feistmantel O (1876) Notes on the age of some fossils of India. Rec Geol Surv India 9:28–42

Halpern M, Linares E (1970) Edad rubidio-estroncio de las rocas graníticas del basamento cristalino del área de Olavarría, Provincia de Buenos Aires, República Argentina. Rev Asoc Geol Argentina 25:303–306

Halpern M et al (1970) Radiometric ages of crystalline rocks from southern South America, as related to Gondwana and Andean geologic provinces. Solid Earth Problems Conference, Buenos Aires

Hart SR (1966) Radiometric ages in Uruguay and Argentina and their implications concerning continental drift. Geological Society of America Annual Meeting, San Francisco

Hartnady C et al (1985) Proterozoic crustal evolution in southwestern Africa. Episodes 8:236–244
Hurley P (1968) The confirmation of continental drift. Sci Am 218:52–64
Hurley PM et al (1964) Test of continental drift by comparison of radiometric ages. Science 157:495–500
Keidel H (1914) Über das Alter, die Verbreitung und die gegenseitigen Beziehungen der verschiedenen tektonischen Strukturen in den argentinischen Gebirgen. International Geological Congress, Toronto
Keidel J (1916) La geología de las sierras de la provincia de Buenos Aires y sus relaciones con las montañas de Sud África y los Andes. *Anales del Ministerio de Agricultura de la Nación*, Sección Geología, Mineralogía y Minería 11:1–78
Keidel H (1938) Über die "Gondwaniden" Argentiniens. Geologische Rundschau 30:148–240
McWilliams MO (1981) Palaeomagnetism and Precambrian tectonic evolution of Gondwana. In: Kröner A (ed) Precambrian Plate Tectonics. Elsevier, Amsterdam, pp 649–687
Medlicott HB, Blanford WT (1879) A Manual of the Geology of India and Burma. Records of the Geological Survey of India, Calcutta
Ortelius A (1570) Theatrum Orbis Terrarum. Gilles Coppens de Diest
Ortelius A (1596) Thesaurus Geographicus
Pflug R (1963) Präkambrische Strukturen in Afrika und Südamerika. Neues Jb Geol P M 7:355–358
Porada H (1979) The Damara-Ribeira orogen of the Pan-African/Brasiliano Cycle in Namibia (South West Africa) and Brazil as interpreted in terms of continental collision. Tectonophysics 57:237–265
Porada H (1989) Pan-African rifting and orogenesis in southern to equatorial Africa and eastern Brazil. Precambrian Res 44:103–106
Siegesmund S, Basei MAS, Oyhantcabal P (2011) Multi-accretional tectonics at the Rio de la Plata Craton margins. Int J Earth Sci 100(2–3):197–694
Smith AG, Hallam A (1970) The fit of the southern continents. Nature 225:139–144
Suess E (1885) Das Antlitz der Erde. Temsky, Vienna
Torquato JR, Cordani UG (1981) Brazil-Africa geological links. Earth-Sci Rev 17:155–176
Umpierre M, Halpern M (1971) Edades Sr–Rb del Sur de la República Oriental del Uruguay. Rev Asoc Geol Argentina 26:133–155
Wegener A (1915) Die Entstehung der Kontinente und Ozeane. Friedrich Vieweg & Sohn, Braunschweig
Wegener A (1929) Die Entstehung der Kontinente und Ozeane, 4th edn. Friedrich Vieweg & Sohn, Braunschweig
Wegener A (2005) Die Entstehung der Kontinente und Ozeane, reprint of 1st edn with handwritten comments by Alfred Wegener and reprint of 4th edn. Gebrüder Borntraeger Verlargsbuchhandlung, Berlin-Stuttgart

Acknowledgements

The authors are greatly indebted to Carlos Cingolani, Víctor Ramos and Mathias Hueck for facilitating Keidel and du Toit's contributions. Craig Robertson is acknowledged for his valuable comments about the origin of the term 'Gondwana'.

The editors gratefully acknowledge the following colleagues for their reviews: Monica Lopez de Lucci, Guido Meinhold, Hartwig Frimmel, Stephen McCourt, Bert De Waele, Carlos Alberto Rosiere, Gerard Germs, Sebastian Oriolo, Pedro Oyhantcabal, Chris Gauert, Mathias Hueck, Thomas Becker, Miguel Basei, Klaus Wemmer, Alex Kisters, Christie Rowe, Carlos Cingolani, Johan de Beer, Siegfried Siegesmund, Wolfram Geissler, Wolf Uwe Reimold, Malte Drobe and Ben Goscombe

Contents

About the Editors

Siegfried Siegesmund is Professor of Geology at the Geoscience Center, Department of Structural Geology and Geodynamics, University of Goettingen, Germany. He began his geological studies at Freiberg University of Mining and Technology. He completed his Ph.D. thesis in 1989 at the University of Kiel, followed by his habilitation in 1995 at the University of Goettingen. He has been a visiting research fellow at the University of Hawaii, University of Harare, University of Laramie, University of Basel, INGEIS Buenos Aires, Universidad de la República (Uruguay), University of São Paulo, University of Granada, University of Oviedo, University of Villa Real, University of Padua, University of San Luis Potosi and others. He has been a member of various international scientific collaborations, including research projects in Antarctica, and was awarded a Heisenberg professorship. His research utilizes an interdisciplinary approach by combining structural geological surveys, geophysical explorations of structures at depth, kinematic studies of shear zones, emplacement of granites, microtectonics, geochronology, neotectonics, geochemistry and provenance studies (i.e. the geodynamic evolutionary development of mountain building processes in general). More recently his geological interests have included aspects of applied geology and geomaterial research (e.g., natural stones in architecture, exploration of dimensional stone deposits and ore deposits) plus geothermal exploration, the deposition of radioactive waste, and petrophysics. He has published more than 25 special issues and monographs, and more than 350 scientific articles and geological maps.

Miguel Angelo Stipp Basei holds a doctorate from 1985 from the Geosciences Institute at the University of São Paulo, where he is currently a full professor. He is a member of the Brazilian Academy of Sciences and a researcher for the National Research Council (CNPq). He was a visiting research fellow for the Open University, UK, from 1988 to 1989 with a specialization in isotope geochemistry, and he developed a postdoctoral program in U-Pb zircon geochronology at the University of Kansas, USA, in 1989. He has a specialization in U-Pb studies in zircon through the systematic SHRIMP technique obtained during several stages at the Australian National University, Canberra in 2000–2006. Since 2009 he has been coordinator of the LA MC ICPMS laboratory of the Geochronological Research Center of the University of São Paulo. He has a scientific interest in topics related to geochronology, geotectonics and structural geology, with a main focus on the tectonic evolution of the Precambrian terrains of the southeastern part of South America and its African counterparts, a topic on which he has already published numerous articles in international journals.

Pedro Oyhantçabal is Professor of Geology at the Universidad de la República of Uruguay and researcher for the Pedeciba and ANII (National Research Council of Uruguay). He obtained his degree in 1982 and his Ph.D. at the University of Göttingen, Germany. He has published more than 30 articles in peer-reviewed journals and has acted as co-editor of a special issue of *International Journal of Earth Sciences*. His interests are in geochemistry and the isotope geology of magmas, geochronology, structural geology, and tectonics. His work currently focuses on the evolution of the Neoproterozoic belts of Uruguay, Southern Brazil, and southwestern Africa.

Sebastian Oriolo is a researcher at the National Scientific and Technical Research Council (CONICET) and the University of Buenos Aires (UBA), Argentina. He obtained his degree in geology in 2012 at the University of Buenos Aires and his Ph.D. in 2016 at the University of Göttingen, Germany. His main interests are structural geology, tectonics, geochronology and petrology, particularly focused on the Precambrian to Paleozoic evolution of Western Gondwana.

Part I

Paleomagnetism, Geophysics and Adamastor

The Assembly of Western Gondwana: Reconstruction Based on Paleomagnetic Data

1

Augusto E. Rapalini

Abstract

In the last two decades some consensus has been reached with regard to the assembly of Gondwana being a long and complex process. Reliable paleomagnetic data are essential to determine the paleogeographic and kinematic evolution of each Gondwana-forming block during its assembly as well as to place chronological constraints on such a process. A review of paleomagnetic data from Western Gondwana blocks indicates that the available Ediacaran to Cambrian database is still scarce and uneven for different cratons, despite clear improvement in the quantity and quality of paleomagnetic information in recent decades. The main constraints placed by the available information are as follows:

- The Río de la Plata and Congo–Sao Francisco cratons were likely already attached by mid-Ediacaran times (*c*. 575 Ma) and not part of Rodinia.
- The Arabian-Nubian Shield was part of proto-Gondwana by 550 Ma and probably even earlier.
- Paleomagnetic constraints are virtually absent for the Kalahari craton.
- Amazonia and West Africa were probably still part of Rodinia and attached to eastern Laurentia by the Early Ediacaran (*c*. 615 Ma), suggesting that a large Ediacaran Clymene Ocean existed between Amazonia and the Congo–Sao Francisco–Río de la Plata block.
- The age of Amazonia amalgamation is poorly constrained by paleomagnetic data as ≥ 525 Ma.
- The accretion of Eastern Gondwana blocks probably occurred in the latest Ediacaran-Cambrian times as suggested by the apparent polar wander path of Australia.

Keywords

Western Gondwana • Paleomagnetism • Ediacaran Cambrian • South America

1.1 Introduction

The assembly of Gondwana in Ediacaran-Cambrian times (e.g., Meert and Lieberman 2008) was a long and complex process that may have lasted well over 50 million years and involved several different ‘orogenies’. Since this process was coetaneous with the major biotic changes occurring during the Earth’s history (i.e., the Cambrian radiation; for detailed references, see Meert and Lieberman 2008), as well as large climatic and environmental changes (Hoffman 1999; Evans 2000; Xiao 2004; Canfield et al. 2007; Meert 2007 and references therein), unravelling the role that these dramatic paleogeographic configuration changes, produced by the assembly of such a continent, had in these events is of paramount importance.

Detailed kinematic and paleogeographic reconstruction of Gondwana assembly is a huge task that must involve several independent disciplines (i.e., geochronology, structural geology, biogeography, biostratigraphy, sedimentology and basin analysis, petrology, geophysics, tectonics etc.). Paleomagnetism is an essential tool for these purposes since it is the only known methodology that provides quantitative determination of paleolatitude and orientation of any continental block at different times (e.g., Butler 1992; Van der Voo 1993). Paleomagnetism is not without caveats and ambiguities, and it only provides a broad paleogeographic picture of distribution of continents along the Earth’s history because its precision will be at its best in a few hundred kilometers. However, it is irreplaceable in producing first-order paleogeographic sketches as well as independently testing many opposing tectonic models. It is also a powerful tool to test whether actualistic climatic and geodynamic processes are valid in Precambrian and Early

A. E. Rapalini (✉)
Departamento de Ciencias Geológicas, Facultad de Ciencias Exactas y Naturales, Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Instituto de Geociencias Básicas, Aplicadas y Ambientales de Buenos Aires (IGEBA), Universidad de Buenos Aires, Buenos Aires, Argentina
e-mail: rapalini@gl.fcen.uba.ar

S. Siegesmund et al. (eds.), *Geology of Southwest Gondwana*, Regional Geology Reviews,
https://doi.org/10.1007/978-3-319-68920-3_1

Paleozoic times (e.g., Kirschvink 1992; Williams 2008; Mitchell et al. 2010).

Many different paleogeographic models for the assembly of Gondwana, based on paleomagnetic data, have been published (e.g., Meert 2003; Collins and Pisarevsky 2005; Meert and Lieberman 2008; Li et al. 2013). Original proposals of a single episode of continental collision (McWilliams 1981) between East Gondwana (East Antarctica, Australia, India and Madagascar) and West Gondwana (South American and African cratons) along the Eastern African orogen have been replaced by models that prescribe a protracted process of collision of several independent crustal blocks (e.g., Powell and Pisarevsky 2002). Although some common ground has been reached among most models, like the complex nature of the amalgamation process that involved more than a dozen different crustal blocks with independent kinematic history, major controversies and uncertainties remain (compare, e.g., Murphy et al. 2013; Johansson 2014). On the basis of these shortcomings are the scarce reliable paleomagnetic data available, despite important progress achieved in the last two decades (e.g., Meert et al. 2001; Sánchez Bettucci and Rapalini 2002; Trindade et al. 2006; Rapalini 2006; Moloto-A-Kenguemba et al. 2009; Gregory et al. 2009; Schmidt et al. 2009; Mitchell et al. 2010; Rapalini et al. 2013, 2015; Schmidt 2014).

In this chapter a brief review of the available paleomagnetic constraints on the Gondwana assembly process, with a main focus on Western Gondwana, is presented.

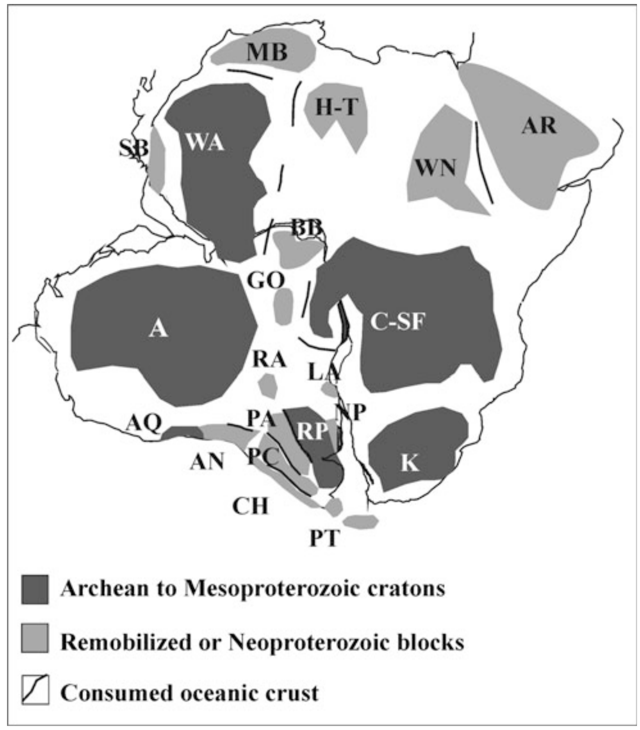

Fig. 1.1 Sketch of main crustal blocks of Western Gondwana in the Neoproterozoic. *A* Amazonia; *AN* Antofalla; *AQ* Arequipa; *AR* Central Arabia; *BB* Borborema, *CH* Chilenia; *C-SF* Congo–Sao Francisco; *GO* Goias; *H-T* Hoggar-Tibesti; *K* Kalahari; *LA* Luis Alves; *MB* Moroccan block; *NP* Nico Perez, *PA* Pampia; *PC* Cuyania; *PT* Patagonian/Malvinas block; *RA* Rio Apa; *RP* Rio de la Plata; *SB* Senegalese block; *WA* West Africa; *WN* West Nile. Modified from Sánchez-Bettucci and Rapalini (2002)

1.2 Main Cratons and Paleomagnetic Database

Figure 1.1 presents a sketch of the main crustal blocks that constitute Western Gondwana. This is composed of five major Archean to Paleoproterozoic cratons—that is, Amazonia, West Africa, Congo–Sao Francisco, Kalahari and Río de la Plata, and many, generally smaller, crustal blocks with Archean to Mesoproterozoic basements but extensively reworked during the Pan-African and Brasiliano orogenies that led to the final assembly of Gondwana. The blocks represented in Fig. 1.1 are not exhaustive because several minor ones have been omitted for clarity of the sketch [e.g., Punta del Este/Cuchilla Dionisio terrane in eastern Uruguay (Bossi and Gaucher 2004) or the Sao Gabriel block in southern Brazil (Saalmann et al. 2006)], as well as long Neoproterozoic thrust and fold belts (e.g., Dom Feliciano, Araguaia, Paraguay, Brasilia, Namara and Gariep) that most probably developed along the margins of some of the larger crustal blocks (e.g., Prave 1996; Brito Neves et al. 2000; Gray et al. 2008; Santos et al. 2008; Oyhantçabal et al. 2009; Pimentel et al. 2011; McGee et al. 2012).

Unravelling the kinematic and paleogeographic evolution of the major cratons in Neoproterozoic-Early Paleozoic times to constrain how the amalgamation of West Gondwana occurred is a major endeavour, let alone if the smaller crustal fragments are considered.

Table 1.1 presents a selection of moderately to highly reliable available paleomagnetic poles for West Gondwana forming pieces for the Ediacaran-Cambrian. Their implications in the models of the continent assembly are discussed below.

1.2.1 The Río de la Plata Craton and Luis Alves Block

Table 1.1 and Fig. 1.2a show that several paleomagnetic poles are available for the Río de la Plata craton for the interval *c*. 600–500 Ma. Although some of them should be considered virtual geomagnetic poles (VGPs) because the small number of samples involved in their computation do not guarantee full average of paleosecular variation (McElhinny and McFadden 2000), and the age of most is loosely bracketed by stratigraphic