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Editors

Geology of Southwest Gondwana

Springer
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

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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
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.
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.

**Öyhantçabal 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 Neo-proterozoic lithostatigraphical 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 migmatisms 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 Rio 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, mineralological 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.

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Contents

Part I Paleomagnetism, Geophysics and Adamastor

1 The Assembly of Western Gondwana: Reconstruction Based on Paleomagnetic Data .................................................. 3
   Augusto E. Rapalini
   1.1 Introduction ................................................................ 3
   1.2 Main Cratons and Paleomagnetic Database ................. 4
      1.2.1 The Río de la Plata Craton and Luis Alves Block .... 4
      1.2.2 The Congo–Sao Francisco Craton ....................... 6
      1.2.3 The Kalahari Craton ........................................ 6
      1.2.4 Amazonia-West Africa .................................... 6
      1.2.5 The Arabian-Nubian Shield .............................. 10
      1.2.6 East Gondwana .......................................... 11
   1.3 Discussion .......................................................... 13
   1.4 Conclusions ....................................................... 16
   References ................................................................... 16

2 An Integrated Geophysical and Geological Interpretation of the Southern African Lithosphere ..................................... 19
   Branko Corner and Raymond J. Durrheim
   2.1 Introduction and Chapter Layout ............................... 19
   2.2 Potential Field Data Sets: An Integrated Interpretation ...... 21
      2.2.1 Magnetic and Gravity Data ............................... 21
      2.2.2 Interpretation Methodology ............................... 22
      2.2.3 Archaean and Palaeoproterozoic Cratons .............. 26
      2.2.4 The Witwatersrand Basin ................................. 31
      2.2.5 Xade Complex ............................................. 32
      2.2.6 Tectonostratigraphic Zones of the Damara-Chobe Orogenic Belt .................................................. 33
      2.2.7 Rehoboth Terrane ......................................... 37
      2.2.8 Deep Neo- and Meso-Proterozoic Basins in Namibia and Angola ......................................................... 38
      2.2.9 West Coast Offshore Domain and the Namibian Passive Volcanic Margin ........................................... 39
      2.2.10 Namaqua-Natal Belt and Its Extension as the Maud Belt in Antarctica ........................................... 40
   2.3 Electrical Resistivity, Magnetotelluric and Regional Seismic Investigations ......................................................... 45
      2.3.1 Introduction .................................................. 45
      2.3.2 Electrical Resistivity and Magnetotelluric Studies .... 45
      2.3.3 Seismic Surveys .......................................... 49
11 The Dom Feliciano Belt in Southern Brazil and Uruguay

Mathias Hueck, Pedro Oyhantçabal, Ruy Paulo Philipp, Miguel Angelo Stipp Basei, and Siegfried Siegesmund

11.1 Introduction

11.2 Santa Catarina Sector

11.2.1 The Cratonic Foreland

11.2.2 The Metavolcano-sedimentary Complex

11.2.3 Neoproterozoic Granitic Magmatism

11.2.4 The Foreland Basin

11.2.5 Deformation History of the Dom Feliciano Belt in Santa Catarina

11.3 Rio Grande do Sul Sector

11.3.1 The Cratonic Foreland

11.3.2 The Metavolcano-sedimentary Complexes

11.3.3 Neoproterozoic Granite Magmatism

11.3.4 The Foreland Basin

11.3.5 Deformation History of the Dom Feliciano Belt in Rio Grande do Sul

11.4 Uruguay Sector

11.4.1 The Cratonic Foreland

11.4.2 The basement of the Punta del Este Terrane

11.4.3 The Metavolcano-sedimentary Complexes

11.4.4 Neoproterozoic Granite Magmatism

11.4.5 The Foreland Basins

11.4.6 Deformation History of the Dom Feliciano Belt in Uruguay

11.5 Discussion and Final Remarks

11.5.1 Deformation Patterns in the Dom Feliciano Belt

11.5.2 Tectonic Evolution of the Dom Feliciano Belt

References

12 The Evolution of the Damara Orogenic System: A Record of West Gondwana Assembly and Crustal Response

Ben Goscombe, David A. Foster, David Gray, and Ben Wade

12.1 Introduction

12.2 Large-Scale Architecture of the Damara Orogenic System

12.2.1 Kaoko Belt

12.2.2 Damara Belt

12.3 Stratigraphy and Provenance of Rock Units

12.3.1 Coastal Terrane Sequences

12.3.2 Sequences Deposited on the Congo Craton

12.3.3 Sequences Deposited on the Kalahari Craton

12.3.4 Foreland Molasse Sequences

12.3.5 Basement Units

12.4 Granite Magmatism

12.4.1 Coastal Terrane

12.4.2 Kaoko Belt

12.4.3 Damara Belt

12.5 Deformation History

12.5.1 Kaokoan Phase: 590–550 Ma

12.5.2 Damaran Phase: 555–508 Ma

References
| 12.5.3 | Transitional Events in the Orogen Core: 516–508 Ma | 327 |
| 12.5.4 | Along Orogen Shortening: 508–505 Ma | 327 |
| 12.5.5 | Vertical Flattening and Orogen Collapse: 505–500 Ma | 327 |
| 12.6 | Metamorphic History | 329 |
| 12.6.1 | Kaoko Belt | 329 |
| 12.6.2 | Damara Belt | 334 |
| 12.7 | Discussion and Conclusions | 336 |
| 12.7.1 | Plate-Tectonic Context of Damara System and West Gondwana Amalgamation | 336 |
| References | 346 |

### 13 The Gariep Belt

Hartwig Ernest Frimmel

| 13.1 | Introduction | 354 |
| 13.2 | Stratigraphy and Basin Architecture | 356 |
| 13.2.1 | Port Nolloth Group | 357 |
| 13.2.2 | Marmora Terrane, Chameis and Oranjemund Groups | 366 |
| 13.3 | Sediment Provenance | 367 |
| 13.4 | Magmatic Evolution | 368 |
| 13.4.1 | Pre-rift Magmatism | 368 |
| 13.4.2 | Syn-rift Magmatism | 370 |
| 13.4.3 | Back-Arc Magmatism | 372 |
| 13.4.4 | Post-orogenic Magmatism | 372 |
| 13.5 | Chemo-, Chrono- and Biostratigraphic Correlation | 373 |
| 13.6 | Deformation and Metamorphism | 376 |
| 13.6.1 | Syndepositional Deformation | 376 |
| 13.6.2 | Synorogenic Deformation and Metamorphism | 377 |
| 13.6.3 | Post-orogenic Deformation | 378 |
| 13.7 | An Integrated Geodynamic Model | 379 |
| 13.7.1 | The Rifting Stage (770–740 Ma) | 379 |
| 13.7.2 | Post-rift Sedimentation (c. 640–580 Ma) | 381 |
| 13.7.3 | The Orogenic Phase (580–540 Ma) | 382 |
| References | 383 |

### 14 The Stratigraphy and Structure of the Western Saldania Belt, South Africa and Geodynamic Implications

Alexander Kisters and Richard Belcher

| 14.1 | Introduction | 387 |
| 14.2 | The Main Geological Characteristics of the Western Saldania Belt | 389 |
| 14.3 | Lithostratigraphic and Structural Relationships in the Western Saldania Belt | 394 |
| 14.3.1 | Lithological Inventory of the Lower Domain: The Swartland Complex | 394 |
| 14.3.2 | Lithological Inventory of the Upper Domain: The Malmesbury Group | 395 |
| 14.3.3 | Klipheuwel Group | 397 |
| 14.3.4 | Granites of the Cape Granite Suite | 399 |
| 14.4 | Structural Geology | 399 |
| 14.4.1 | D1 Structures and Fabrics of the Swartland Complex | 399 |
| 14.4.2 | D2 Regional Folding and Associated Strains | 401 |
| 14.4.3 | D2 Strike-Slip Faults | 403 |
| 14.5 | Discussion | 404 |
| 14.5.1 | Swartland Complex | 404 |
| 14.5.2 | Malmesbury Group | 404 |
| 14.5.3 | Deformation of the Fore Arc (D2) | 405 |
| 14.5.4 | The Deeper Structure of the Western Saldania Belt | 407 |
15 Suturing Gondwana in the Cambrian: The Orographic Events of the Final Amalgamation

Renata da Silva Schmitt, Rafael de Araújo Fragoso, and Alan Stephen Collins

15.1 Introduction ........................................................................................................... 411
15.2 Gondwana Amalgamation ...................................................................................... 414
15.2.1 Eastern Gondwana Orogens (Including the EAO) ......................................... 415
15.2.2 Western Gondwana Orogens (Pan-African–Brasiliano Events) ...................... 418
15.3 Ediacaran-Cambrian Orogens in SW Gondwana—the South Atlantic Orogenic System ................................................................................................................. 420
15.3.1 670–575 Ma Orogens ......................................................................................... 420
15.3.2 575–480 Ma Orogens ......................................................................................... 420
15.4 Discussion ............................................................................................................. 422
15.4.1 Correlating Ediacaran-Cambrian Orogens Throughout Gondwana ............... 423
15.4.2 Do the Internal Western Gondwana Ediacaran-Cambrian Orogens Represent Closure of Oceanic Realms? ................................................................. 423
15.5 Conclusion .......................................................................................................... 424

References .................................................................................................................. 424

16 Untangling the Neoproterozoic-Early Paleozoic Tectonic Evolution of the Eastern Sierras Pampeanas Hidden in the Isotopical Record

Mónica G. López de Luchi, Carmen I. Martínez Dopico, Klaus Wemmer, and Siegfried Siegesmund

16.1 Introduction .......................................................................................................... 434
16.2 Geological Background of the Main Basement Units of the Eastern Sierras Pampeanas ............................................................................................................. 434
16.3 Time Constraints on the Pampean Metamorphism .............................................. 441
16.4 Time Constraints for the Famatinian Metamorphism .......................................... 442
16.5 Magmatism in the Eastern Sierras Pampeanas ...................................................... 442
16.5.1 Ediacaran to Cambrian Granitoids .................................................................... 442
16.5.2 Ordovician Magmatism .................................................................................... 443
16.5.3 Devonian to Lower Carboniferous Magmatism .............................................. 444
16.5.4 Neoproterozoic-Ordovician (Ultra-)Mafic Rocks ............................................. 444
16.6 Isotopic Constraints for the Neoproterozoic-Early Paleozoic Geodynamic Evolution of the Gondwana Margin ................................................................. 445
16.6.1 Sm–Nd Fingerprints for the Metamorphic Rocks ............................................. 445
16.6.2 Sm–Nd Fingerprints for the Migmatic Rocks .................................................. 445
16.7 Detrital Zircon Constraints on Protoliths of the Metaclastic Sequences ................ 448
16.8 Orogenic Events of the Eastern Sierras Pampeanas .............................................. 451
16.8.1 Pampean Orogeny .......................................................................................... 451
16.8.2 Famatinian Orogeny ....................................................................................... 456
16.8.3 Achalian Orogeny ......................................................................................... 457
16.9 Concluding Remarks and Critical Topics for a Renewed Proposal for the Early Paleozoic Tectonic Evolution of the Eastern Sierras Pampeanas ................................. 457

References .................................................................................................................. 460

Part IV Special Topics

17 The Iron Formations of Southern Africa ..................................................................... 469

Albertus J. B. Smith
17.1 Introduction ................................................ 470
17.2 The Classification of Iron Formations ............................ 470
  17.2.1 Texture. ............................................ 470
  17.2.2 Mineralogy. ......................................... 471
  17.2.3 Stratigraphic Setting. .................................. 474
17.3 Meso- to Neoarchean Algoma-Type Iron Formations of Southern Africa .................................................... 474
  17.3.1 Algoma-Type Iron Formations in the Greenstone Belts of the Kaapvaal Craton 474
  17.3.2 Algoma-Type Iron Formations in the Greenstone Belts of the Zimbabwe Craton 475
  17.3.3 A Note on Iron-Rich Metasediments in the Limpopo Belt 477
17.4 Mesoarchean Superior-Type Iron Formations of Southern Africa ............................................. 477
17.5 Neoarchean-Paleoproterozoic Superior-Type Iron Formations of Southern Africa ............................................. 479
17.6 Mid-Proterozoic Iron-Rich Metasediments of Southern Africa ............................................. 480
17.7 Neoproterozoic Rapitan-Type Iron Formations of Southern Africa ............................................. 481
17.8 Selected Geochemical Characteristics of the Iron Formations of Southern Africa ............................................. 483
17.9 Depositional Models and the Geological Significance of the Iron Formations of Southern Africa 485
17.10 The Economic Significance of the Iron Formations of Southern Africa ............................................. 487
References ....................................................... 488

18 The Iron Formations of the South American Platform ................... 493
Carlos Alberto Rosière, Adriana Heimann, Pedro Oyhantçabal, and João Orestes Schneider Santos
18.1 Introduction ................................................ 493
18.2 Iron Formations: Main Characteristics ............................ 494
18.3 Iron Formation-Hosted Iron-Ore Deposits 495
18.4 Iron Formations of SW Gondwana 495
  18.4.1 The Amazon Craton. .................................... 496
  18.4.2 The São Francisco Craton .................................. 500
  18.4.3 The Tocantins Province: Archean Greenstone Belts, Paleoproterozoic Terranes and Neoproterozoic Belt of the Western Border of the São Francisco Craton 506
  18.4.4 The Borborema Province .................................. 508
  18.4.5 The Paraguay Belt .................................... 508
  18.4.6 The Nico Pérez Terrane of Southern Brazil and Uruguay 508
  18.4.7 Rio de la Plata Craton, Piedra Alta Terrane, Southwestern Uruguay ................................................................. 517
  18.4.8 The Dom Feliciano Belt .................................... 518
18.5 Depositional Record of IFs in Southwestern Gondwana 519
18.6 Concluding Remarks ......................................... 520
References ....................................................... 521

19 The Glaciations in South America ................................... 527
Daniel G. Poiré, Lucia E. Gómez Peral, and María J. Arrouy
19.1 Introduction ................................................ 527
19.2 Glacial Deposits in South America ............................................. 528
  19.2.1 Northern Paraguay Belt in the Amazonia Paleocontinent 528
19.3 Phantom Glacial Deposits in South America 531
  19.3.1 Tandilia System in the Rio de La Plata Craton 531
19.4 Other Examples of Tillites, Phantom Glacial Deposits and Indeterminate Diamictites in South America 536
References
22.6.1 Introduction ........................................ 605
22.6.2 Colenso Fault ....................................... 606
22.6.3 Piketberg-Wellington Fault ............................ 607
22.7 Discussion and Final Remarks ................................. 607
   22.7.1 The Role of Shear Zones in the Brasiliano–Pan-African Orogeny ................................. 607
   22.7.2 Structural Inheritance and Shear Zone Reactivation During the Phanerozoic ............... 608
References .................................................................. 608

23 The African Metallotects of Southwest Gondwana .......................... 615
Gregor Borg and Christoph Gauert
23.1 Introduction ................................................................ 615
23.2 Central African Copperbelt .................................... 616
23.3 The Kalahari Copper Belt in Namibia and Botswana ............... 621
23.4 The West Congo Belt ............................................. 632
23.5 The Matchless Belt in Namibia .................................. 636
23.6 Ore Deposits of the Coastal Damaran Orogenic Belts ................ 637
23.7 The Tsongoari–Omupokko Pb–Cu–Ba–Zn–Ag Prospects, Kaokoveld, NW-Namibia ........... 638
23.8 The Rosh Pinah, Skorpion, Gergarub Pb-Zn District ............... 641
   23.8.1 Rosh Pinah Mine ........................................ 643
   23.8.2 The Hypogene Skorpion Sulphide Zn (Cu–Pb) Deposit ...... 645
   23.8.3 The Gergarub Pb–Zn Prospect ......................... 647
23.9 The O’okiep Copper District .................................. 649
23.10 The Aggeneys Cu–Zn Deposits Within the Western Namaqua (-Natal) Metamorphic Belt .... 652
   23.10.1 The Aggeneys District (Gamsberg, Black Mountain, Broken Hill) ......................... 652
23.11 Felsic and Exotic Intrusion-Related Sn-/W-, U-, Li-, REE- and Au Deposits .................... 655
   23.11.1 Tin-Tungsten Deposits ................................ 656
   23.11.2 Uranium Deposits .................................... 661
   23.11.3 Rare Earth Element Deposits ....................... 663
   23.11.4 Lithium (Niobium-Tantalum-Feldspar) Deposits ............ 664
   23.11.5 The Navachab Gold-Skarn and Vein-Type Gold Deposit, Namibia ............................. 665
23.12 Late Tectonic Deposits, Omitiomire and Similar Pan-African Cu Deposits .................... 668
23.13 Conclusions .................................................. 668
References .................................................................. 668

24 The Impact Record of Southwest Gondwana .......................... 677
Wolf Uwe Reimold, Natalia Hauser, and Alvaro P. Crósta
24.1 Introduction .................................................. 677
24.2 The Terrestrial Impact Record .................................. 678
24.3 The African and South American (SW Gondwana) Impact Record ............................. 683
24.4 Discussion ..................................................... 685
24.5 Conclusions .................................................. 686
References .................................................................. 687
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