



Preface

Evolution of the East African and related orogens, and the assembly of Gondwana

Neoproterozoic closure of the Mozambique Ocean collapsed an accretionary collage of arc and microcontinental terranes and sutured East and West Gondwana along the length of the East African Orogen (Fig. 1). This special issue of *Precambrian Research* brings together articles on aspects of the East African Orogen's tectonic history to provide a better understanding of this ancient mountain belt and its relationships to the evolution of crust, climate, and life at the end of Precambrian time. The formation of Gondwana at the end of the Precambrian and the dawn of the Phanerozoic represents one of the most fundamental problems being studied in *Earth Sciences* today. It links many different fields, and there are currently numerous and rapid changes in our understanding of events related to the assembly of Gondwana. One of the most fundamental and most poorly understood aspects of the formation of Gondwana is the timing and geometry of closure of the oceanic basins which separated the continental fragments that amassed to form the Late Neoproterozoic supercontinent. It appears that the final collision between East and West Gondwana most likely followed the closure of the Mozambique Ocean, forming the East African Orogen. The East African Orogen encompasses the Arabian–Nubian Shield in the north and the Mozambique Belt in the south (Fig. 1). These and several other orogenic belts are commonly referred to as Pan-African belts, recognizing that many distinct belts in Africa and other continents experienced deformation, metamorphism, and magmatic activity spanning the period of 800–450 Ma. Pan-African tectonothermal activity in the Mozambique Belt was broadly contemporaneous with magmatism, metamorphism and deformation in

the Arabian–Nubian Shield. The difference in lithology and metamorphic grade between the two belts has been attributed to the difference in the level of exposure, with the Mozambican rocks interpreted as lower crustal equivalents of the juvenile rocks in the Arabian–Nubian Shield. Recent geochronologic data indicate the presence of two major Pan-African tectonic events in East Africa. The East African Orogeny (800–650 Ma; Stern, 1994) represents a distinct series of events within the Pan-African of central Gondwana, responsible for the assembly of greater Gondwana. Collectively, paleomagnetic and age data indicate that another later event at 550 Ma (Kuunga Orogeny) may represent the final suturing of the Australian and Antarctic segments of the Gondwana continent (Meert and van der Voo, 1996).

Three main topics are the focus of ongoing studies by the contributors to this volume. The first is to better understand the timing of Gondwana's amalgamation, a topic that is central to the debate relating global-scale tectonics to biologic and climatic change. The second is to constrain the configuration of cratons within Rodinia and mechanisms by which Gondwana formed. The third concerns the very nature of the East African Orogen, the youngest collision zone between East and West Gondwana: what are its continental and oceanic constituents? When did it form? What is the geometry of the major collision zones that bound its accreted terranes? All of these issues are central to a current, much-debated hypothesis of Neoproterozoic geology: Can the dramatic biologic, climatic, and geologic events that mark Earth's transition into the Cambrian be linked to the distribution of continents to the breakup and reassembly of a supercontinent?

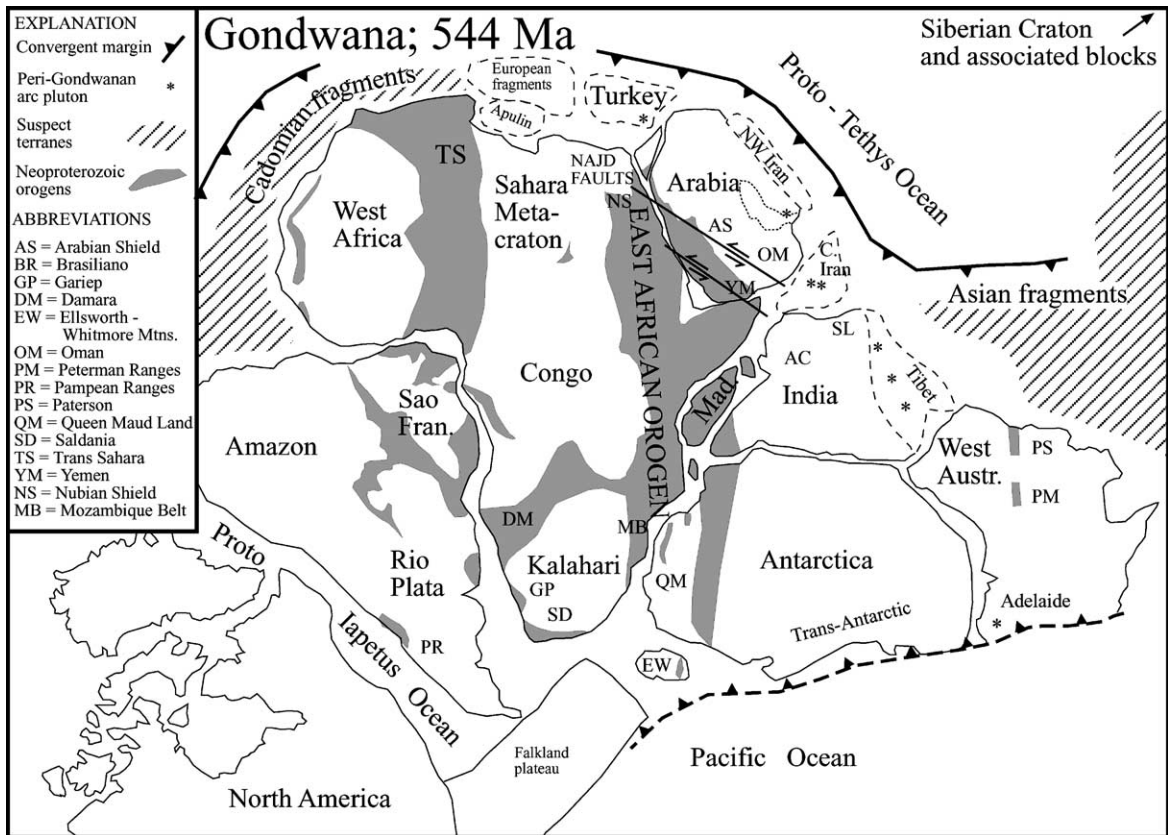


Fig. 1. Map of Gondwana at the end of Neoproterozoic time showing the general arrangement of different tectonic elements discussed in this volume. Map modified after Unrug (1997), Powell et al. (1990, 1994), de Wit et al. (1988).

This is an important question, broad in scope and fundamental in nature. The range of papers in this issue cover these topics across a geographic area that extends over more than 7000 km, and a period of time that spans more than 500 million years. Many workers have integrated field, structural, geochronological, and satellite remote sensing studies with other data to derive the unique view of the East African Orogen represented by this volume.

This special issue of *Precambrian Research* is arranged geographically from south to north, which also imparts a general arrangement from the highest metamorphic grade rocks, generally deformed by the earliest tectonic structures, through to later, lower-grade metamorphic rocks and younger structures in the northern part of the orogen. The first three papers focus on the part of the orogen exposed

in Madagascar, where a controversy surrounds issues related to the timing of collision, location of sutures, vergence of early-generation structures, dip of subduction zones, and affinity (East or West Gondwana, or neither) of sedimentary sequences. Fernandez and others present a field-based structural and geochronologic synthesis of the critical Itremo Group, suggesting it is disposed in a westward-directed fold-and-thrust belt that thrust relatively low-grade Itremo Group rocks over higher-grade rocks to the west. Fernandez and his co-workers suggest that contacts between circa 800 Ma plutons are in the form of early thrusts, and recognize that younger, circa 565 Ma plutons cut the tectonic fabrics. Collins and others synthesize their field-based studies of the same region. They suggest that the region experienced E–W contraction during a deformation event that occurred between 637

and 560 Ma, followed by a non-coaxial deformation that occurred between 530 and 515 Ma in the form of E-verging thrusting. Collins and his co-workers suggest that the boundary between the Itremo Group and underlying Archean–Proterozoic gneisses (their Antanarivo Block) is an extensional structure named the Betsileo shear zone. They also suggest that the main suture between East and West Gondwana lies to the east of the Itremo Group along the Betsimisaraka suture, across which the Dharwar Craton of India was separated from the Congo/Tanzania/Bangweulu Craton of Africa, and the Antanarivo Block of Madagascar. Goncalves and others present a structural synthesis of the mafic–ultramafic Andriamena unit in north-central Madagascar. They suggest that the Andriamena unit is a lower crustal fragment of a continental margin magmatic arc generated by closure of the Mozambique Ocean, then thrust to the east over gneissic basement after 630 Ma. Structures related to continued E–W shortening, occurred after emplacement of the Andriamena unit, are suggested to be related to convergence of the Madagascar–India–Sri Lanka block with the Australia–Antarctica block into the Cambrian.

Hargrove and others synthesize the tectonic evolution of the Zambezi orogenic belt in northern Zimbabwe. The E–W-trending Zambezi orogen records interactions of the Congo and Kalahari cratons, and connects at a high angle to the N-trending East African Orogen. In the eastern part of the orogen, S-verging, thick-skinned thrusting has inverted a circa 795 Ma Neoproterozoic supracrustal sequence that is now structurally overlain by circa 1830 Ma lower-crustal granulites consisting of metagabbro and meta-anorthosite. Granitic orthogneisses in the thrust stack have ages of 1050 and 870 Ma. U–Pb zircon and titanite metamorphic ages indicate that the S-directed thrusting occurred at 550–530 Ma, during the final assembly of Gondwana.

Beyth and others investigated aspects of late-orogenic evolution of the East African Orogen in northeast Ethiopia and Eritrea using field work and orbital remote sensing studies. They examine a group of 800 Ma metasediments and metavolcanics structurally overlying an 850 Ma high-grade assemblage of metasediments and orthogneiss in eastern Eritrea. They estimate that metamorphic conditions in the high-grade assemblage reached 700 °C at 12 kbar

(40 km), suggesting that crustal thicknesses reached 70 km during the height of orogenesis. Rapid exhumation between 640 and 545 Ma is interpreted to represent orogenic collapse.

Neoproterozoic rock assemblages of the Arabian–Nubian Shield cover approximately 3×10^6 km² in northeastern Africa, western Arabia and Sinai. The Nubian Shield encompasses parts of Egypt, Sudan, Ethiopia, Eritrea, and Somalia, whilst the Arabian Shield stretches in Saudi Arabia, Yemen, and Oman. The Saharan metacraton occupies a poorly exposed region west of the Nubian Shield in western Sudan, Chad, Central African Republic, Cameroon, Nigeria, Niger, and Libya. Abdelsalam and others describe the geology of this region, and relate it to events in the East African Orogen. They recognize three Neoproterozoic deformation events including early (700–650 Ma) emplacement of S- to SE-verging nappes consisting of ophiolites and passive margin sediments. E–W shortening produced by collision of the Saharan metacraton with the Arabian–Nubian Shield at 650–590 Ma formed N- to NE-trending folds in the eastern part of the craton. North to NNW-trending sinistral strike-slip shear zones developed at 590–550 Ma, and are kinematically linked to N-striking fold belts. North striking extensional shear zones may be related to late (post-550 Ma) extensional collapse of the orogen.

The main units in the Arabian–Nubian Shield comprise Neoproterozoic metasedimentary rocks and migmatites, metavolcanic suites, serpentinites and dismembered ophiolite complexes, gabbro-diorite-tonalite complexes, and unmetamorphosed volcanic and pyroclastic sequences that are extensively intruded, especially in the north, by batholithic monzonite–granodiorite–granite complexes (Stern, 1994). The recognition of ophiolites and their dismembered fragments, together with the identification of chemically distinct island-arc volcanic and plutonic complexes in the Arabian–Nubian Shield, has led to general agreement that this part of the continental crust developed through horizontal crustal accretion during closure of the Mozambique Ocean. The presence of highly dismembered ophiolite suites which define suture zones that can be traced southward from the Arabian–Nubian Shield into the Mozambique Belt supports the idea that collision was the dominant orogenic mechanism throughout the East African Orogen.

The Arabian–Nubian Shield ophiolites demonstrate that oceanic crust formed and was partially preserved and that ophiolite and other nappes traveled tens to hundreds of kilometers, indicating that horizontal translation was an important aspect of crustal shortening. Stein presents an alternate but not incompatible view on the evolution of the Arabian–Nubian Shield based primarily on geochemical studies of volcanic and plutonic rocks. He suggests that the high rate of crustal growth inferred for the Arabian–Nubian Shield may be attributable to the accretion of magmas originally derived from a mantle plume head, and swept into Mozambique Ocean subduction zones during the accretion of oceanic plateaus. This mechanism would transform plume-mantle into juvenile lithospheric mantle via the subduction process, reconciling plume and subduction models for the growth of the shield. Volesky and others integrate field and orbital remote sensing studies for the Wadi Bidah mineral district in southwestern Saudi Arabia. They demonstrate the utility of Landsat Thematic Mapper and Advanced Space-Borne Thermal Emission Radiometer remote sensing data for regional structural syntheses. They show that massive sulfide mineral deposits in the area are stratabound and related to a group of felsic volcanics.

From the Sinai, Brooijmans and others present geothermobarometric evidence to support an earlier model for a metamorphic core complex in the Wadi Kid area. Uplift of the core occurred during an upper greenschist to upper amphibolite metamorphic conditions. They postulate that this purported metamorphic core complex formed during late-orogenic extension post-dating orogenic collapse. The doming is thought to have occurred along with widespread intrusion of post-orogenic granitic rocks. Similar evolution of core complexes have been described for metamorphic domes in the SE Desert of Egypt. El-Shafei and Kusky present a detailed structural analysis of the Feiran–Solaf metamorphic belt in the southern Sinai Peninsula. High-grade predominantly gneiss and migmatites of sedimentary origin are folded by early NW-striking intrafolial isoclinal folds and cut by early mylonite zones, then refolded by NW-striking recumbent folds. The high grade metamorphic rocks form the core of a dome with migmatites in the center, surrounded by amphibolite-facies rocks. The early generations of folds are interpreted as related to

accretion of the metasediments (accretionary prism?) between colliding arcs. El-Shafei and Kusky considered a younger N-striking generation of upright folds to be related to E–W shortening and NW-directed tectonic escape along NW-striking shear zones, perhaps reflecting a deep crustal level of the Najd Fault System. Interestingly, whereas El-Shafei and Kusky relate the late-orogenic structures to folding associated with the Najd Fault System, Brooijmans and others relate the similar dome in the Wadi Kid area to core complex formation.

Jarrar and others examine the abundant late- and post-orogenic intrusives of Jordan, in the northernmost segment of the East African Orogen. The Aqaba Suite (600–640 Ma) ranges from gabbro to high-silica granite, follows a high-K differentiation trend and represents the main crust-forming stage in SW Jordan. Jarrar and his co-workers use geochemical modeling to show that the Aqaba Suite represents melts generated in a subduction zone environment, with variable amounts of melting of spinel lherzolite (for the gabbro) and high degrees of melting of subducted oceanic crust for the granitoids. The volumetrically smaller Araba Suite (560–600 Ma) cuts a regional unconformity, and has characteristics of within-plate magmatism. Jarrar and others further note the change in magma types in Jordan from convergent margin magmas (Aqaba Suite), to a bimodal suite of rift-related magmas characterized by shallow (feldspar controlled) fractionation.

Collision between East and West Gondwana left an oceanic free-face in the north. Extension of the Arabian–Nubian Shield toward this free-face led to the formation of rifted basins in NE Africa and Arabia during latest Neoproterozoic time. The continental collision first led to crustal thickening and uplift, and continued with escape tectonics until the end of Precambrian. [Burke and Sengor \(1986\)](#) suggested that the NW-trending Najd Fault System was associated with escape tectonics, due to the collision between East and West Gondwana along the East African Orogen. However, the concentrations of granulitic rocks in the Mozambique Belt and their absence from the Arabian–Nubian Shield support the interpretation that crustal thickening, erosion, and intensity of deformation increased to the south. On the other hand, occurrences of granulite as far north as central Sudan suggests at least two episodes of granulite-facies

metamorphism, Archean and Neoproterozoic (Stern and Dawoud, 1991).

Johnson presents a comprehensive review of post-amalgamation basins in the Arabian–Nubian Shield, all formed after the main accretionary events in the shield. The circa 670–650 Ma Murdama basins are up to 8 km thick and cover more than 70,000 km², perhaps reflecting deposition in foreland and intermontane collisional basins, as well as in incipient pull-apart basins of the Bani Ghayy Group. The Murdama basins were folded at 650 Ma then unconformably overlain by 640–620 Ma rocks of the Jurdhawiyah Group and Hibshi Formation in fault-controlled basins. E–W shortening formed additional N-trending folds in these basins. This was followed by the deposition of the Jibalah Group in pull-apart basins along the Najd Fault System between 580 and 570 Ma, with sedimentation including isolated lake deposits. The Jibalah basins record the transition from the Neoproterozoic into the Cambrian, marked in most places in the Arabian Shield by an unconformity overlain by the Saq sandstone.

References

- Burke, K., Sengor, C., 1986. Tectonic escape in the evolution of the continental crust. In: M. Barazangi, L. Brown (Ed.), *Reflection Seismology: The Continental Crust*. Am. Geophys. Union, Geodyn. Ser. 14, Am. Geophys. Union, Washington, DC.
- Meert, J.G., van der Voo, S., 1996. Paleomagnetic and ⁴⁰Ar/³⁹Ar study of the Sinyai Dolerite, Kenya: implications for Gondwana assembly. *J. Geol.* 104, 131–142.
- Powell, C.Mc.A., Li, Z.X., Thrupp, G.A., Schmidt, P.W., 1990. Australian Palaeozoic palaeomagnetism and tectonics—I: Tectonostratigraphic terrane constraints from the Tasman fold belt. *J. Struct. Geol.* 12, 553–565.
- Powell, C.Mc.A., Preiss, W.V., Gatehouse, C.G., Krapez, B., Li, Z.X., 1994. South Australian record of a Rodinian epicontinental basin and its mid-Neoproterozoic breakup to form the Palaeo-Pacific Ocean. *Tectonophysics* 237, 113–140.
- Stern, R.J., 1994. Arc assembly and continental collision in the Neoproterozoic East African Orogen: implications for consolidation of Gondwanaland. *Annu. Rev. Earth Planet. Sci.* 22, 319–351.
- Stern, R., Dawoud, A.S., 1991. Late Precambrian (740 Ma) charnockite, enderbite, and granite from Jebal Moya, Sudan: a link between the Mozambique Belt and the Arabian–Nubian Shield? *J. Geol.* 99, 648–659.
- Unrug, R., 1997. Rodinia to Gondwana: the geodynamic map of Gondwana supercontinent assembly. *GSA Today* 7 (1), 1–6.
- de Wit, M.J., Jeffry, M. Bergh, Nicolayson, L., 1988. Geological map of sectors of Gondwana, reconstructed to their disposition ~150 Ma, American Association of Petroleum Geologists and the University of Witwatersrand, Tulsa.

Timothy M. Kusky*

*Department of Earth and Atmospheric Sciences
Saint Louis University, 3507 Laclede Ave.*

St. Louis, MO 63103, USA

* Corresponding author

Mohamed Abdelsalam, Robert J. Stern

Geosciences Department

University of Texas at Dallas, Box 830688

Richardson, TX 75083-0688, USA

Robert D. Tucker

Department of Earth and Planetary Sciences

Washington University, Campus Box 1169

One Brookings Drive

St. Louis, MO 63130-4899, USA