The formation and evolution of Africa from the Archaean to Present: introduction

DOUWE J. J. VAN HINSBERGEN[1,2]*, SUSANNE J. H. BUITER[1,2,3], TROND H. TORSVIK[1,2,3,4], CARMEN GAINA[1,2,3] & SUSAN J. WEBB[4]

[1]*Physics of Geological Processes, University of Oslo, Sem Sælands vei 24, NO-0316 Oslo, Norway*

[2]*Center for Advanced Study, Norwegian Academy of Science and Letters, Drammensveien 78, 0271 Oslo, Norway*

[3]*Centre for Geodynamics, Geological Survey of Norway (NGU), Leiv Eirikssons vei 39, 7491 Trondheim, Norway*

[4]*School of Geosciences, University of the Witwatersrand, WITS 2050 Johannesburg, South Africa*

**Corresponding author (e-mail: d.v.hinsbergen@fys.uio.no)*

The African continent preserves a long geological record that covers almost 75% of Earth's history. The Pan-African orogeny (*c.* 600–500 Ma) brought together old continental kernels (or cratons such as West African, Congo, Kalahari and Tanzania) forming Gondwana and subsequently the supercontinent Pangea by the late Palaeozoic (Fig. 1).

The break-up of Pangea since the Jurassic and Cretaceous, primarily through the opening of the Central Atlantic (e.g. Torsvik *et al.* 2008; Labails *et al.* 2010), Indian (e.g. Gaina *et al.* 2007; Müller *et al.* 2008; Cande *et al.* 2010) and South Atlantic (e.g. Torsvik *et al.* 2009) oceans and the complicated subduction history to the north gradually shaped the African continent and its surrounding oceanic basins. Many first-order questions of African geology are still unanswered. How many accretion phases do the Proterozoic belts represent? What triggers extension and formation of the East African Rift on a continent that is largely surrounded by spreading centres and, therefore, expected to be mainly in compression? What is the role of shallow mantle and edge-driven convection (King & Ritsema 2000)? What are the sources of the volcanic centres of Northern Africa (e.g. Tibesti, Dafur and Afar) and can they be traced to the lower mantle? Is the elevation of Eastern and Southern Africa caused by mantle processes? What is the formation mechanism of intracratonic sedimentary basins, such as the Taoudeni Basin on the West African Craton and the Congo Basin (e.g. Hartley & Allen 1994; Giresse 2005)? How do sedimentation and tectonics interact (Burke & Gunnell 2008)? Can we reconstruct this elevation and its impact on climate evolution (e.g. Wichura *et al.* 2011)?

This special volume contains 18 original contributions about the geology of Africa. It celebrates African geology in two ways. First, it celebrates multidisciplinary Earth Science research, highlighting the formation and evolution of Africa from 18 different angles. Second, this volume celebrates the work of Kevin Burke and Lewis Ashwal. We hope that this 'Burke and Ashwal' volume portrays the wide range of interests and research angles that have characterized these two scientists throughout their careers working in Africa and studying African geology (Ashwal & Burke 1989; Burke 1996; Burke *et al.* 2003).

Content of the volume

This volume focuses on the formation of Africa as a coherent continent, from the formation of some of the oldest continental crust known today in the Kaapvaal Craton (de Wit *et al.* 1992) to billions of years of collisions and arc-accretions, amalgamating these old continental fragments (Hoffman 1991; Stern 1994; Zhao *et al.* 2002; Torsvik 2003) into Gondwana and the supercontinent Pangea. The contributions in this volume cover most of the African continent (Fig. 2), span >2 Ga of its history and approach its complex history from a geophysical, geological, geochemical and physical geographical point of view.

In recent years, the importance of deep mantle processes as a trigger for surface volcanism including world-changing (?) Large Igneous Province emplacement (Burke & Torsvik 2004; Burke *et al.* 2008), diamond-bearing kimberlite formation (Torsvik *et al.* 2010) and dynamic topography

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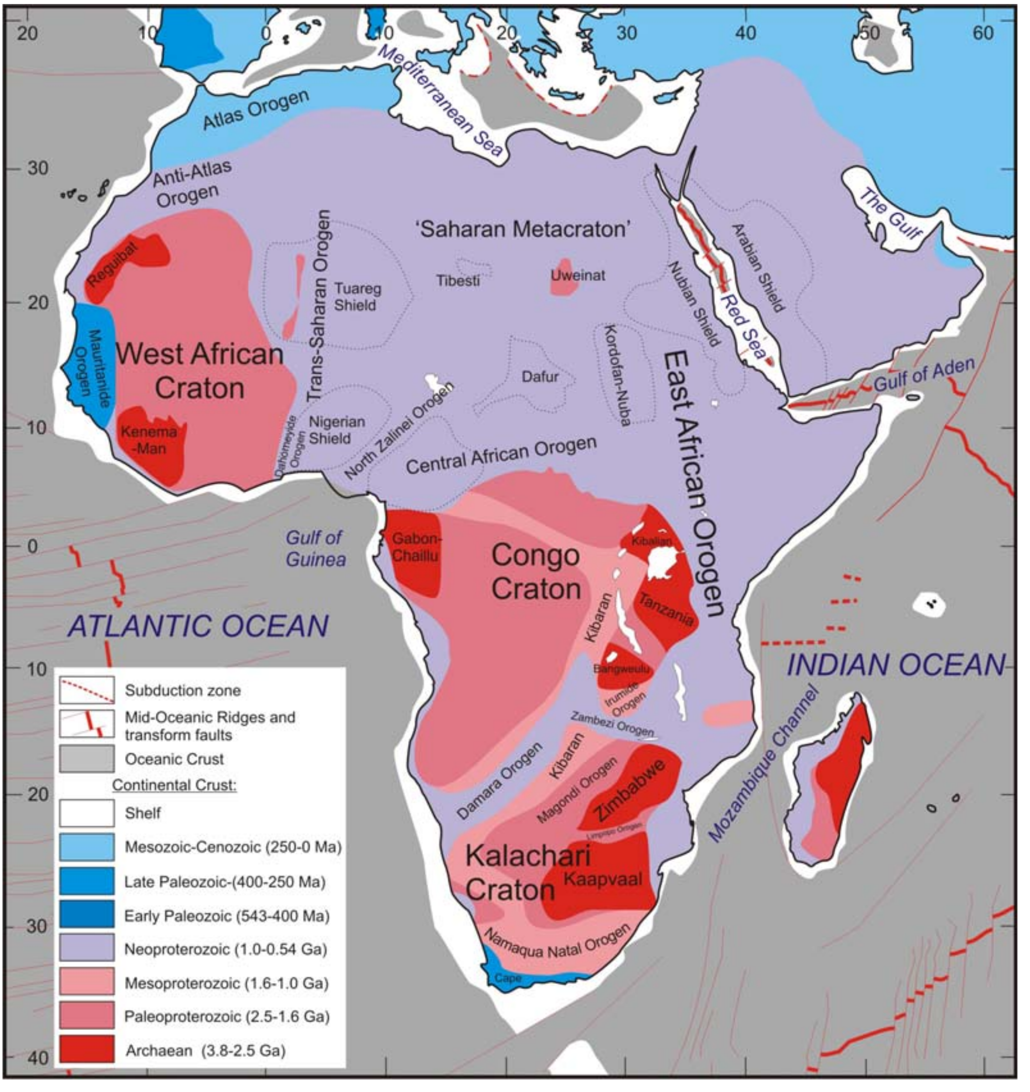

Fig. 1. Age of African crustal basement (after Gubanov & Mooney 2009). The ages are the time of crustal formation or the time of thermal or tectonic crustal reworking.

(e.g. Lithgow-Bertollini & Silver 1998) has become evident. Several contributions in this volume shed new light on these processes and their geological and environmental effects.

Part 1: The making of the African crust: The Archaean–Palaeozoic phases

The first part of this volume covers the formation of Africa from old cratons through assembly in the Pan-African orogeny to the formation of Gondwana.

Letts *et al.* (2011) provide new, high-quality palaeomagnetic poles for *c.* 2 Ga old rocks from the Kaapvaal Craton. By comparing their new results with published information, they demonstrate that the Kaapvaal Craton was not associated with high rates of apparent polar wander during the *c.* 2.1–1.9 Ga interval. Van Schijndel *et al.* (2011) provide new detrital zircon data from sandstones in the Rehoboth province of Namibia that identify three dominant periods of continental crust formation: between 1.3–1.1, 2.0–1.8 and 3–2.7 Ga, the latter of which was previously unknown. Key *et al.* (2011) report an extensive

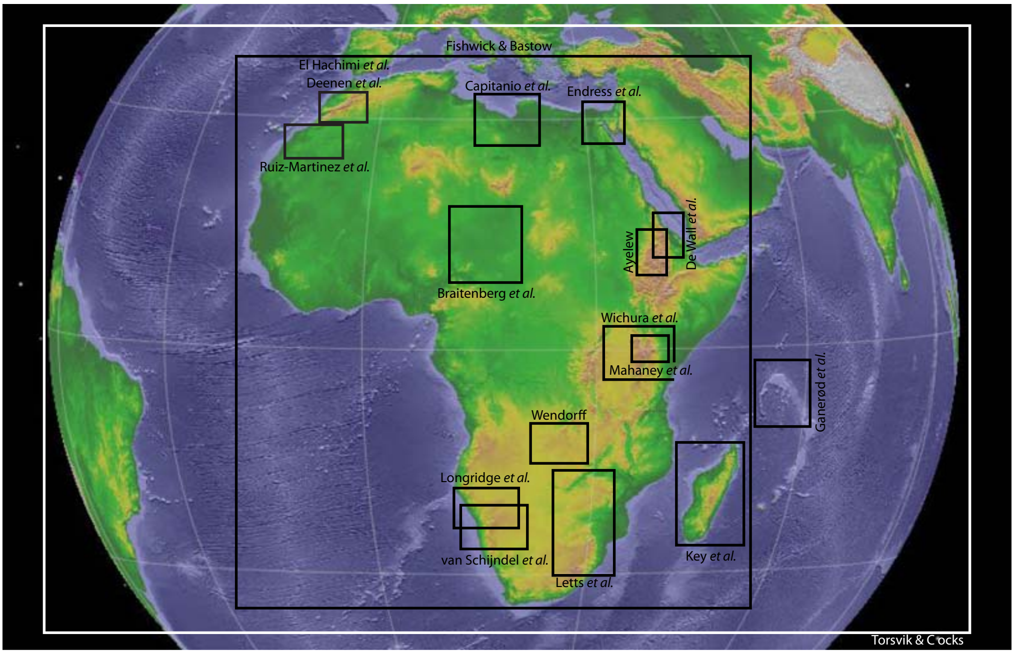

Fig. 2. Study areas covered in this volume.

geological survey of the basement rocks of Madagascar, providing an overview of the five Archaean to Proterozoic basement blocks that are recognized on the island. They review the Neoproterozoic collision and amalgamation history of the Madagascar segment of the East Africa–Antarctica Orogen, which was finalized during the Terminal Pan-African Event 560–490 Ma ago. Wendorff (2011) provides new insights into the history of the Lufilian Arc, which formed as a result of the Pan-African collision between the Kalahari and Congo cratons. The structural and stratigraphic evolution of this belt shows evidence for two previously unidentified rift and foreland basins. De Wall *et al.* (2011) study the metamorphic and tectonic history of the Terminal Pan-African Event in Ethiopia. They provide new metamorphic and magnetic fabric data from the Central Steep Zone, a transpressional belt that can be traced into Eritrea. They argue that the deformation and metamorphism in their study area results from closure of the Mozambique Ocean and the final assembly of Gondwana. Longridge *et al.* (2011) provide a detailed structural geological and geochronological study of the Central Zone of the Pan-African Damara orogen in Namibia. They unravel a history of crustal thickening, heating of the mid-crust, exhumation and orogen-parallel extension between *c.* 540 and 500 Ma. Torsvik & Cocks (2011) provide nine new palaeogeographic maps of Gondwana between 510 and 250 Ma. They detail the locations of passive and active margins around Gondwana throughout the Palaeozoic, continental shelves, evaporite deposits, volcanism and glaciations, including those affecting Africa and Arabia.

Part 2: Africa since the break-up of Pangea: The Mesozoic–Cenozoic phases

The papers in the second part discuss events from the break-up of Pangea to the late Cenozoic. During this time Africa moved relatively slowly (Burke 1996). El Hachimi *et al.* (2011) focus their attention on the Central Atlantic Magmatic Province (CAMP) that was emplaced around 200 Ma. The mantle plume that led to its emplacement probably triggered Pangea dispersal (Burke & Dewey 1973). El Hachimi *et al.* (2011) study the morphology, internal architecture and emplacement mechanisms of CAMP lavas in the Argana Basin of Morocco. They demonstrate that the emplacement mechanisms are in line with continental flood basalt facies models. Deenen *et al.* (2011) take a stratigraphic approach to the CAMP, and use magnetostratigraphic and cyclostratigraphic techniques to correlate the Moroccan segment of the CAMP to their counterparts on the NW side of the Atlantic Ocean in Canada and the United

States. They provide new age constraints and correlations on the largest Large Igneous Province that led to the break-up of Pangea and the formation of Africa as a continent. Ruiz-Martinez *et al.* (2011) provide a new palaeomagnetic pole for a *c.* 93 Ma sedimentary section in SW Morocco, which forms the first Turonian palaeopole for Africa. Given their large dataset, they can correct their results for compaction-induced shallowing of the inclination and provide a reliable pole. They discuss their results within the context of Africa's apparent polar wander path for the Cretaceous. Ganerød *et al.* (2011) provide new palaeomagnetic, U/Pb and $^{40}Ar/^{39}Ar$ data from continental flood basalts on the Seychelles (Indian Ocean), demonstrating an age range of *c.* 67–61 Ma. These ages are consistent with an origin related to the Deccan traps in India. Palaeomagnetic results (after correction for a vertical axis rotation) confirm that the last Gondwana fragment (India and the Seychelles) was split after this event, and the Seychelles microcontinent became part of the African plate again. Ayelew (2011) provides new Rb/Sr age determinations of bimodal basalt–rhyolite volcanism of *c.* 20 Ma from Ethiopia, related to the continental flood basalt province associated with the Afar plume. Using Sr and Nd isotopic compositions, he argues that the rhyolites formed due to fractional crystallization of mantle-derived basaltic magmas similar in composition to the exposed flood basalts. Endress *et al.* (2011) study *c.* 24 Ma old intraplate magmatism in Egypt and demonstrate that their lavas are geochemically similar to those of the Afar plume and to the subcrustal lithosphere. They speculate that the basalts could be derived from magmas that come from the edges of the African Large Low Shear-wave Velocity Province (LLSVP) at the core–mantle boundary and/or from small-scale convection at the base of the upper mantle. The Egyptian magmas found their way to the surface utilizing incipient rift-related structures of the Red Sea. Wichura *et al.* (2011) address the notoriously difficult issue of the determination of palaeo-elevation of continental crust. They provide an elegant analysis in which they use the emplacement characteristics of a 350 km long middle Miocene lava in Kenya to determine a minimum slope required for its outflow. This enables them to determine a minimum elevation of the source region in Kenya in middle Miocene times of 1400 m. Mahaney *et al.* (2011) provide a unique, multidisciplinary analysis of 5.5–5.2 Ma palaeosols preserved between lavas near Mt Kenya. They use these palaeosols to infer the continental climate history of near-equatorial Africa during the last 5 Ma, demonstrating generally dry conditions during the late Miocene followed by punctuated humid conditions during the Pliocene and Quaternary. Capitanio *et al.* (2011) study the Sirte Basin in northern Lybia, a peculiar extensional domain that has historically been seismically active and has experienced Pliocene extension. They correlate this extensional deformation with the contemporaneous Sicily Channel rift, and argue that the strong slab-pull gradients of the subducted African plate in the central Mediterranean region have tectonic effects up to 1400 km south of the subduction zone.

Part 3: Current state of the African crust and lithosphere

The last two papers of this volume use gravity and seismic data to provide an image of the present-day state of the African lithosphere and upper mantle. Braitenberg *et al.* (2011) use high-precision global gravity models to provide images of a sub-Saharan lithospheric structure in Chad. They argue that this structure is probably a metamorphic or magmatic belt within the Saharan Megacraton. Fishwick & Bastow (2011) provide a review of seismological observations of the African lithosphere and upper mantle, providing an observational basis for the testing of geodynamical modelling studies that aim to explain Africa's complex topography. They discuss their overview within the context of the African LLSVP, small-scale convection and the role of the sublithospheric mantle.

African geology through the eyes of Kevin Burke and Lewis Ashwal

Kevin Charles Antony Burke was born on 13 November 1929 in London (England). He attended University College London, where he earned a BSc in 1951 and a PhD two years later. For two decades (1961–1981), Kevin held university teaching and research positions in Ghana, Korea, Jamaica, Nigeria, the United States and Canada. He met and worked with Tuzo Wilson at the University of Toronto in the early 1970s (Burke & Wilson 1972; Wilson & Burke 1972), an obvious turning point in Kevin's career. Since 2002 he has been an Honorary Professor at the School of Geosciences at the University of the Witwatersrand where he has been teaching plate tectonics and African geology during their winter months, and he still teaches at the University of Houston, Texas.

Kevin has made fundamental and lasting contributions to our understanding of the origin and evolution of the lithosphere on Earth and other planets. His influence has been grand and global in its reach and, as a synthesizer of global geology and global geological processes, Kevin has few peers. It is almost impossible to quantify the breadth of his innovation and knowledge from the oldest remnants in the Archaean to those ongoing today. It was Kevin Burke who coined the term 'Wilson Cycle' for the succession of continental rifting, subsidence and ocean opening, initiation of subduction and ocean closure and eventual continent–continent collision. Kevin was a pioneer in suggesting that Precambrian orogens like the Grenville are the eroded products of Himalayan-style collisions (Dewey & Burke 1973; Burke *et al.* 1976*a*). He was the first to propose that the Archaean auriferous Witwatersrand sedimentary sequence is a foreland basin (Burke *et al.* 1986). He also proposed in the early 1970s that greenstone belts, present in nearly all Archaean regions, are allochthonous volcano-sedimentary packages originally formed as marginal basins, ocean islands and arcs and were later thrust onto older continents (Burke *et al.* 1976*b*). Kevin Burke never stops to amaze the Earth Science community with his innovative and provocative ideas. Over the last eight years he has re-energized his long-lasting interest in mantle plumes. In 2004 Kevin discovered that large igneous provinces from the past 200 million years must have originated as plumes from the edges of the LLSVPs near the core-mantle boundary (Burke & Torsvik 2004; Burke *et al.* 2008). This surprising observation implies that deep-mantle heterogeneities have not changed much for hundreds of millions of years. Recognizing long-term stability of lower-mantle structures and the corresponding parts of the gravity field also fundamentally influences our thinking of how the Earth's moment of inertia and rotation may have changed over geological times (Steinberger & Torsvik 2010).

Lewis David Ashwal was born on 16 November 1949 in New York City (USA) and earned a PhD from Princeton University in 1979. The topic of Lew's PhD thesis was petrogenesis of massif-type anorthosites (Ashwal 1982; Ashwal & Wooden 1983) and he would later become the world leader in the understanding of the origin of anorthosites, a subject of heated theoretical debate for many decades (Ashwal & Burke 1989; Ashwal 1993). Lew's first position from 1978–1980 was post-doctoral research associate at NASA, Johnson Space Center, followed by 9 years as staff scientist at the Lunar and Planetary Institute in Houston. During the Lunar and Planetary Institute period (1980–1989), Lew clearly interacted with his boss (Kevin) but they only wrote one paper together, which was on the topic of African lithospheric structure, volcanism and topography (Ashwal & Burke 1989).

Lew has made fundamental contributions to petrology, mineralogy and geochemistry of anorthosite and related rocks, layered mafic intrusions, origin and evolution of planetary crusts, Precambrian geological history, origin of magmatic ore deposits, the role of fluids in igneous and metamorphic processes, meteorites and their parent bodies, abundance and distribution of crustal radioactivity, thermal and petrologic aspects of granulite metamorphism, geology of Madagascar and other Indian Ocean continental fragments and the Rodinia supercontinent and Gondwana assembly and break-up.

Meteorites and their parent bodies occupied Lew's mind in the late 1970s and early 1980s. In a 1981 groundbreaking paper Chuck Wood and Lew, by the process of elimination, suggested that meteorites of the so-called SNC group (Shergottites–Nakhlites–Chassignites) were derived from a differentiated planetary body, most likely Mars (Wood & Ashwal 1981). The difficulty of blasting material off a planetary surface and into an Earth-crossing orbit made planets such as Venus and Mercury unlikely sources, and chemical comparisons with Lunar samples (collected by the Apollo missions) also eliminated the moon as a potential source; Mars remained the only viable possibility. Lew and colleagues published a follow-up manuscript in 1982 where they demonstrated that petrologic, geochemical and isotopic evidence were inconsistent with an asteroidal origin and concluded that Mars remained the most likely parent body for SNC meteorites; they were later proven correct (Ashwal *et al.* 1982).

In 1990, Lew became Professor of Geology at the Rand Afrikaans University (RAU), Johannesburg, South Africa. He served RAU with distinction for more than 10 years, but in 2001 he moved across the road to the School of Geosciences at the University of the Witwatersrand, where he is an enduring Professor and Director of the African Lithosphere Research Unit. Lew has written several books and hundreds of scientific papers, reports and essays; listing all of his contributions to geology is undoable. We would be negligent if we did not mention Lew's genuine passion for Africa, not only for her geology but also for her inhabitants; as an educator Lew is legendary.

Lew and Kevin have remained friends and colleagues since the Lunar and Planetary Institute days in the 1980s. They still work, converse and passionately argue with each other. Both have enjoyed great scientific success in diverse scientific fields. They have collaborated on projects probing into the world's oldest rocks, the deep continental crust and global characterization of the ancient continents and lithosphere. Joint papers cover diverse subjects such as characterization of terrestrial anorthosites, lithospheric delamination on Earth and Venus, African lithosphere structure and volcanism, identification of old sutures guided by deformed alkaline rocks and carbonatites, Proterozoic mountain building and, most recently, plumes from the deepest mantle (Ashwal & Burke 1989; Burke *et al.* 2003, 2007; Leelanandam *et al.* 2006; Ashwal *et al.* 2007; Torsvik *et al.* 2010). Many more papers are likely to appear in the coming years and we wish them a happy 140th birthday.

This volume was initiated at a conference held in Johannesburg, South Africa in November 2009, honouring the work of Kevin Burke and Lewis Ashwal. We thank all conference participants for their contributions and stimulating discussions. We thank the Geological Society Publishing House and especially Tamzin Anderson, Angharad Hills and Randell Stephenson for their help with the publication of this volume. The editors appreciate financial support from Statoil for 'The African Plate' project.

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