Int J Earth Sci (Geol Rundsch) (2014) 103:579–595
DOI 10.1007/s00531-013-0974-5

ORIGINAL PAPER

The provenance of northern Kalahari Basin sediments and growth history of the southern Congo Craton reconstructed by U–Pb ages of zircons from recent river sands

Andreas Gärtner · Ulf Linnemann · Mandy Hofmann

Received: 21 January 2013 / Accepted: 22 October 2013 / Published online: 9 November 2013

Abstract The southern Congo Craton is widely overlain by Meso- to Cenozoic sediments of the northern Kalahari Basin, which hamper any correlation of basement units. The latter are represented by the Archaean Angola and Kasai Blocks, while the southern cratonic margin is framed by several Meso- to Neoproterozoic orogenic belts. For provenance analysis of the sedimentary cover and reconstruction of the main zircon-forming events, we studied zircons from recent sediments of the largest rivers at the southern margin of the Congo Craton. U–Pb zircon ages suggest a major amount of the sediments to originate from E Lufilian and Kibaran Belts, while input from the S Damara Belt seems to increase to the W. Ages related to the Angola Block were only noticed in the westernmost parts of the working area, which is not in accordance with the SE-trending drainage pattern, proposed to have been onset during the Cretaceous. Thus, it is assumed that the Meso- to Cenozoic sedimentary cover extended further west than today prior to the Mesozoic to Neogene uplift of the Angola Block and that subsequent erosion exhumed the basement stepwise from west to east. A recurrent destabilisation of the southern margin of the Congo Craton at ~2.7, 1.9, 1.0 and 0.6 Ga is supposed to be represented by major peaks in the age distribution pattern of the total amount of concordant zircons. This is in accordance with similar studies in adjacent areas. Additionally, the obtained data fit well to several hypothesised major events during the supercontinent cycle.

Keywords Southern Congo Craton · Episodic crustal growth and reworking · Pan-African orogeny · Northern Kalahari Basin · U–Pb zircon dating

Introduction

The working area includes the Archaean Angola and Kasai Blocks, both of which are poorly known and represent the only known basement outcrops of the southern Congo Craton (De Carvalho et al. 2000; De Waele et al. 2008). The southern margin of the latter is postulated to extend from the Atlantic coast of northernmost Namibia to the western parts of Zambia and the Democratic Republic of Congo. In these regions, the craton is limited to the south and east by the Mesoproterozoic to Cambrian Kaoko, Damara, Lufilian and Kibaran Belts (Fig. 1). As wide areas of the southern Congo Craton are overlain by the Cretaceous to Cenozoic sedimentary cover of the Kalahari Basin (Haddon and McCarthy 2005), there is a lack of data for the basement and most of the following sedimentary succession for major parts of this area (De Waele et al. 2008). Although there have been many studies concerning the sediments of the Kalahari Basin since the early twentieth century (summarised in Haddon and McCarthy 2005; Ringrose et al. 2008), the question of provenance still remains unclear (Haddon 2005).

Electronic supplementary material The online version of this article (doi:10.1007/s00531-013-0974-5) contains supplementary material, which is available to authorized users.

A. Gärtner (✉) · U. Linnemann · M. Hofmann
GeoPlasma Lab, Sektion Geochronologie, Museum für Mineralogie und Geologie, Senckenberg Naturhistorische Sammlungen Dresden, Königsbrücker Landstraße 159, 01109 Dresden, Germany
e-mail: andreas.gaertner@senckenberg.de

U. Linnemann
e-mail: ulf.linnemann@senckenberg.de

M. Hofmann
e-mail: mandy.hofmann@senckenberg.de

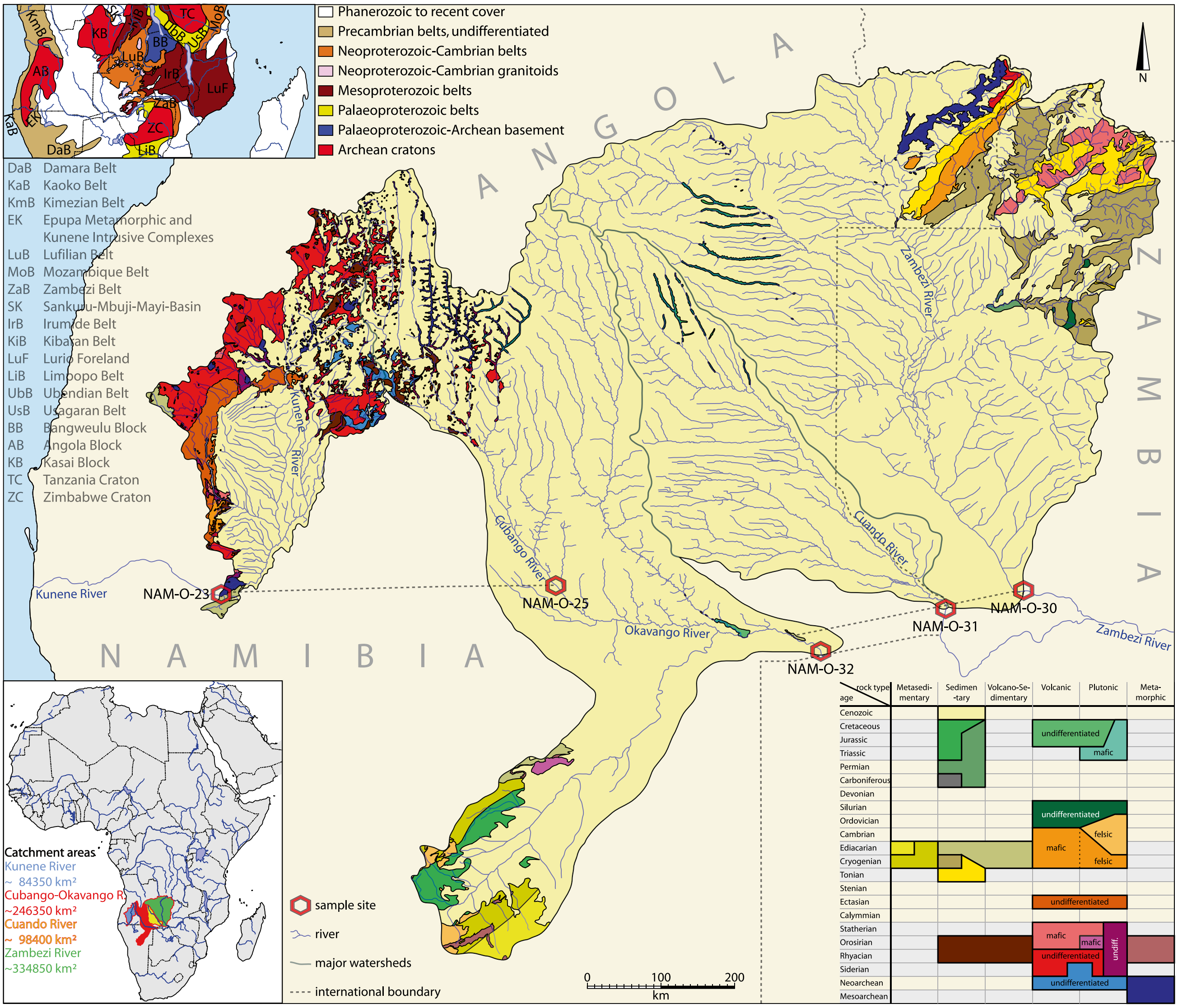

Fig. 1 Overview of the areal distribution and surface geology of the catchment areas of the Kunene, Cubango–Okavango, Cuando and Zambezi River systems upstream of the sample localities (compiled from De Carvalho 1974; Delor et al. 2007; Miller and Schalk 1980; Milési et al. 2004; Milési et al. 2006). The legend specifies the main rock types in the working area by their estimated age and their petrologic characteristics

Therefore, we studied zircons from the sediments of the largest recent rivers, which drain almost the entire southern margin of the Congo Craton.

A second issue of this work is to reveal a possible growth history of the southern Congo Craton. Former studies suggest an episodic crustal reworking at the southern margin of the adjacent Bangweulu Craton (De Waele et al. 2006b). This is also a possible scenario for the working area, which should be proven using detrital zircons of recent river sands, too. The method of tracing the episodic growth of continental crust using zircons from recent river sediments was already introduced by Rino et al. (2004, 2008) and several other authors (e.g. Yang et al. 2009; Wang et al. 2011; Schärer et al. 2012). River sands are assumed to be representative of the age distribution pattern of the rocks within the catchment area (Rino et al. 2008; Bradley 2011). They also may include recycled zircons of lithological units which do not crop out anymore (Belousova et al. 2010). Bradley (2011) states expressly that these assumptions can only be considered for ancient cratons, as we do for the southern Congo Craton.

During the entire analysing processes, we got some additional data such as width, length, roundness and surface characteristics from the zircon grains. They are all given in the supplementary tables 2 to 6 and can be used for further studies. For example, we tested the hypothesised

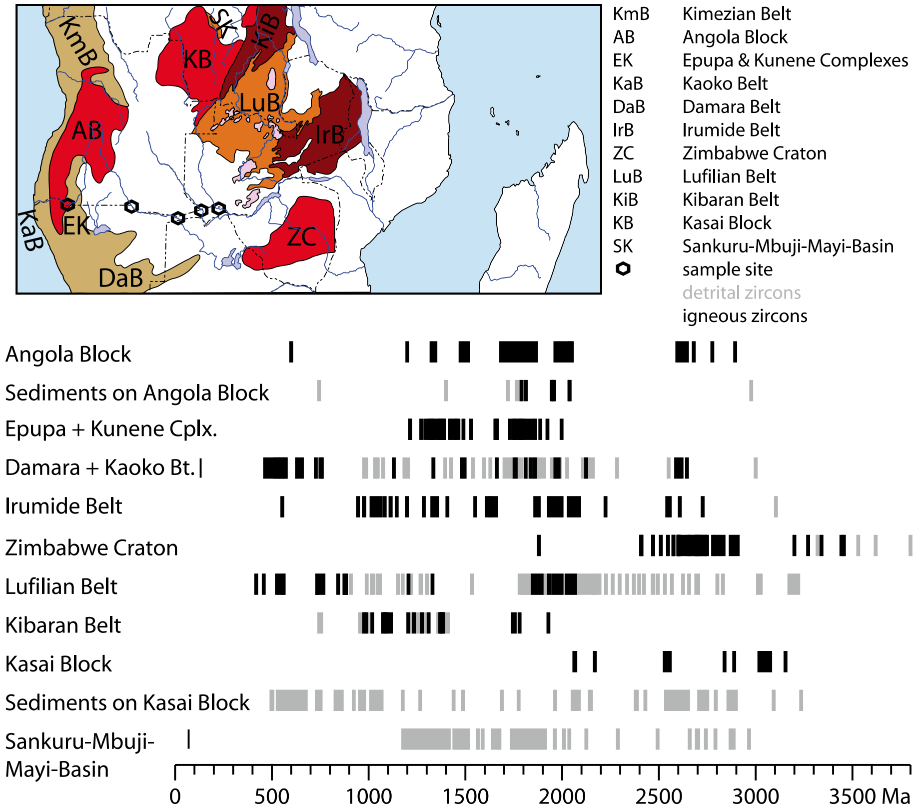

Fig. 2 Igneous and detrital zircon age distribution patterns of the Archaean to Neoproterozoic cratons and belts surrounding the working area (data compiled from Alkmim and Martins-Neto 2012; Batumike et al. 2009; De Carvalho et al. 2000; Delpomdor et al. unpublished data; Haddon 2005; Johnson and Rivers 2004; Kampunzu et al. 2000; Kröner et al. 2010; Lobo-Guerrero Sanz 2005; McGee et al. 2012; Ngoyi et al. 1991; Pedreira and De Waele 2008; Pereira et al. 2011; Prendergast and Wingate 2012; Rainaud et al. 2003, 2005; Rapela et al. 2011; Rollinson and Whitehouse 2011; Schmitt et al. 2012; Tack et al. 2010; Thover et al. 2006; Torrealday et al. 2000, 2007; Walraven and Rumvegeri 1993; Wendorff and Key 2009; Wigand et al. 2004 and references therein)

effect of hydrodynamic fractionation of zircon age populations, suggested by Lawrence et al. (2011) and Yang et al. (2012).

This paper proposes a model for the provenance of the northern Kalahari sands and the growth history of the southern margin of the Congo Craton, which is based on multiple U–Pb ages and morphological characteristics of zircons from recent river sands.

Geological setting

The Kunene, Cubango–Okavango, Cuando and Zambezi Rivers drain the southern margin of the Congo Craton. This region comprises two poorly known Palaeoproterozoic to Archaean blocks, the Angola Block in the west and the Kasai Block in the north-east (De Waele et al. 2008). Both blocks are separated by the northern part of the Kalahari Basin (Haddon and McCarthy 2005) and the southern part of the Congo Basin (De Waele et al. 2008). They both are covered by Late Cretaceous to Cenozoic sediments. Further tectonic units surrounding the working area are the Epupa Metamorphic and Kunene Intrusive Complexes, the Kaoko and Damara Belts, the Zimbabwe Craton, the Lufilian and Kibaran Belts as well as the sedimentary Sankuru–Mbuji–Mayi Basin (Fig. 1). Known zircon ages of these tectonic units are given in Fig. 2.

The Archaean to Mesoproterozoic Cratons and intrusive complexes

The Angola and Kasai Blocks are located within the catchment areas of the studied rivers. Both are poorly known, and scarcity of data as well as separation by the Meso- to Cenozoic sedimentary cover makes correlation impossible (De Waele et al. 2008).

The Angola Block is composed of orthogneisses, granites, migmatites, charnockites, norites, greenstones, quartzites and schists (De Carvalho et al. 2000; Delor et al. 2007; De Waele et al. 2008). Oldest known zircons that are interpreted to originate from the Angola Block displayed ages around 2,977 Ma (McCourt et al. 2004; Kröner et al. 2010). A major metamorphic event is suggested to have taken place during a 2,900–2,700-Ma period (Neoarchaean), when granulite facies metamorphism occurred (De Carvalho et al. 2000; De Waele et al. 2008; Pereira et al. 2011). This interpretation is supported by several Rb–Sr and Sm–Nd data summarised in De Carvalho et al. (2000) and De Waele et al. (2008). Palaeoproterozoic zircon ages obtained from the Angola Block are possibly related to a metamorphic event at ~2,050 Ma (De Carvalho et al. 2000) and the intrusion of the northern Kunene Intrusive and Epupa Metamorphic Complexes (De Waele et al. 2008). The same has to be assumed for the few known Mesoproterozoic zircon ages (Rapela et al. 2011). Youngest reported zircon ages at around 600 Ma are supposed to be related to metamorphism during the Pan-African orogeny (De Carvalho et al. 2000).

At its south-eastern margin, the Angola Block was intruded by anorthosites, granites, gabbros and dolerites of the Kunene Intrusive Complex (Slejko et al. 2002; Kröner et al. 2010). This complex is supposed to be subdivided into a pre-Eburnean northern part and a Kibaran southern part (De Carvalho et al. 2000; Mayer et al. 2004). Rb–Sr whole-rock isochrones for the northern part, given by De Carvalho et al. (2000), range between 1,847 ± 62 and 2,443 ± 49 Ma. This is in accordance with the reported K–Ar ages of 1,964 ± 61–2,157 ± 43 Ma for plagioclase from anorthosite and olivine gabbro (Mayer et al. 2004). Zircon ages are not yet known from the northern Kunene Intrusive Complex. For the southern part, there are several zircon ages between 1,371 ± 3 and 1,385 ± 25 Ma (Drüppel et al. 2000, 2007; Mayer et al. 2004). They are accompanied by Sm–Nd mineral isochrones from 1,470 ± 25 to 1,319 ± 28 Ma (Mayer et al. 2004), supporting the assumption of a Kibaran age.

The Epupa Metamorphic Complex is adjacent to the southern margin of the Angola Block and was also intruded by the southern Kunene Intrusive Complex around 1,375 Ma (Gleißner et al. 2012). Main rock types are granitoid gneisses, which are mostly migmatised. The known U–Pb zircon ages range from 1,757 ± 4 to 1,861 ± 7 Ma (Kröner et al. 2010). Additional Nd isotopic data indicate separation from the depleted mantle at about 2,000–2,400 Ma. Hence, an Archaean component as in the Angola Block is very unlikely (Kröner et al. 2010). Both the Kunene Intrusive and the Epupa Metamorphic Complexes are overlain by undeformed Neoproterozoic sediments of the Damara Supergroup, which is interpreted as a sign of the absence of deformation during the Pan-African orogeny (Brandt et al. 2007; Gleißner et al. 2012).

A possible separate crustal unit at the southern and eastern margins of the Kunene Intrusive Complex and the Epupa Metamorphic Complex is represented by the Epembe unit (Seth et al. 2003; Kröner et al. 2010). U–Pb ages of zircon from granulitic rocks are between 1,510 and 1,520 Ma for prograde crystal growth during metamorphosis. Inherited cores yield ages from 1,635 to 1,810 Ma, which is interpreted as age of the different protoliths (Seth et al. 2003). Another unit of uncertain origin is represented by the adjacent ~1,731 Ma (Calymmian) to round 1,997 Ma (Orosirian) rocks of the Orue Unit, which were intruded by red granites at about 1,374 Ma and metamorphosed between 1,340 and 1,320 Ma (Seth et al. 2005).

The Kasai Block comprises granulites (tonalitic) gneisses, granites, granodiorites, amphibolites, gabbronorites, gabbro-charnockites and migmatites (De Carvalho et al. 2000; De Waele et al. 2008; Batumike et al. 2009). Dated zircons with maximum ages of about 3,154 Ma suggest at least Mesoarchaean formation of parts of this block (Key et al. 2001; Lobo-Guerrero Sanz 2005; Rainaud et al. 2005). Granitoids with whole-rock Rb–Sr ages of between 3,490 and 3,330 Ma (Cahen et al. 1984) and Hf-isotope data on detrital zircons, suggesting a crustal age of around 3,600 Ma (Batumike et al. 2009), lead to the assumption of an even older, Palaeoarchaean, origin of the Kasai Block (De Waele et al. 2008). The few known zircon ages (Fig. 2) are between 3,154 and 2,058 Ma, with main populations around 2,540, 2,880 and 3,050 Ma (De Carvalho et al. 2000; Key et al. 2001; Lobo-Guerrero Sanz 2005; Rainaud et al. 2005). The sediments of the Sankuru–Mbuji–Mayi Basin also show Palaeoproterozoic zircon age patterns (Delpomdor, unpublished data, Fig. 2), which are very similar to the known barcode of the Kasai Block and its sediments.

Augen gneisses located in NW Botswana yielded ages around 2,050 Ma (Singletary et al. 2003). They are possibly related to synchronous events at the Angola and Kasai Blocks although the sedimentary cover prevents any correlation.

Unlike the Angola and Kasai Blocks, the Zimbabwe Craton also comprises zircons of Palaeo- and Eoarchaean ages (Rollinson and Whitehouse 2011). Major magmatic events occurred during almost the entire Neo- and Mesoarchaean (Rollinson and Whitehouse 2011; Prendergast and Wingate 2012). Younger events are not known, except some doleritic sills of Orosirian age (Söderlund et al. 2012).

Meso- and Neoproterozoic Belts

The Kibaran Belt is mostly described as a Mesoproterozoic orogen trending NE from the Katanga region of the Democratic Republic of Congo to southern Uganda. But recent studies redefined the nomenclature. Thus, the Katanga region, including the Kibaride Belt in SE Democratic Republic of Congo, is meant while using the term Kibaran Belt (Kokonyangi et al. 2006; Tack et al. 2010). The belt is composed of metasedimentary rocks and minor metavolcanic rocks. They are intruded by mostly S-type granites of Ectasian to Tonian (1,000–1,400 Ma) age (Kokonyangi et al. 2004; Tack et al. 2010) representing the main period of the Kibaran event (Rainaud et al. 2005). The oldest reported age of a zircon from the Kibaran Belt is 1,929 ± 21 Ma, which is supposed to be derived from the Palaeoproterozoic basement (Tack et al. 2010; Fig. 2). A southward extension to Botswana is hypothesised by Kampunzu et al. (1999, 2000), who found zircon age populations in the siliciclastic Ghanzi Group between 627 and 1,748 Ma with major peaks at ~1,100 and ~1,360 Ma. Zircons at ~1,750 Ma are interpreted as exotic detrital grains of possible north Namibian origin.

The NE-trending Damara Belt and the NW-trending Kaoko Belt are two parts of the Damara orogen (Schmitt et al. 2012), which is situated at the SW margin of the Congo Craton. Both belts are multiphased orogens with a complex growth history (Frimmel et al. 2011). The recent configuration is a product of the collision between three palaeocontinents—Rio de la Plata, Kalahari and Congo Cratons—during the amalgamation of Gondwana in Neoproterozoic to Cambrian times (Rapela et al. 2011; Schmitt et al. 2012). The peak of collision is supposed to be around 530 Ma, which is indicated by numerous intrusions of granitic and syenitic composition (Schmitt et al. 2012). Goscombe et al. (2005) revealed a metamorphic event between 535 and 505 Ma. Youngest known ages are of around 460 Ma (Veevers 2007) and are possibly related to post-tectonic extension. Nevertheless, older orogenic events and several inliers are preserved. Magmatism at ~670–640 Ma and metamorphism at 655–645 Ma and ~585 Ma are known from the Kaoko Belt (Goscombe et al. 2005; Goscombe and Gray 2008; Oyhantçabal et al. 2011). Ages at about 750 Ma were reported by several authors (Hoffman et al. 1996; Hanson 2003; Halverson et al. 2005; Jung et al. 2007; Frimmel and Miller 2009) and references therein. They are also reported by McGee et al. (2012) from a pegmatite of the Welwitschia Inlier and are interpreted as rift-related. Sediments of the Toekems Basin yielded a widespread pattern of zircon ages (McGee et al. 2012) with main peaks at 950–1,080, 1,620–1,860 and 2,040–2,165 Ma. Several Neo- to Mesoproterozoic igneous and metamorphic events from the Kaoko and Damara Belts are also given in Goscombe and Gray (2008) and in Luft et al. (2011). Zircon ages around 2,000 Ma are published by Hoal et al. (2000) for the Tsumkwe region of the mafic Grootfontein Complex. The orthogneisses in the Kaokoveld (Seth et al. 1998) contained the oldest known zircons with ages up to 2,645 Ma. The oldest reported detrital zircons are dated at roughly 3,000 Ma (Rapela et al. 2011).

The Lufilian Belt, which is situated between the NE Kalahari and SE Congo Cratons, forms a north-directed thrust-and-fold arc. This belt contains several Neoproterozoic volcanosedimentary sequences (Frimmel et al. 2011) and supracrustal sedimentary successions of ca. 5–10 km thickness (Cailteux et al. 2005). The deposition of the sediments is supposed to have started around 880 Ma (Armstrong et al. 2005; Wendorff and Key 2009) and lasted at least until ~735 Ma. Two sedimentary groups contain diamictites that are interpreted as tillites correlating with the Sturtian and possibly Marinoan glacial events (e.g. Binda and van Eden 1972; Batumike et al. 2007). Extensional magmatism occurred in the course of the break-up of Rodinia between 765 and 735 Ma (Key et al. 2001; Ernst et al. 2008; Wendorff and Key 2009). Deformation likely happened between 700 and 500 Ma (Cosi et al. 1992; Key and Armstrong 2000; Porada and Berhorst 2000; Batumike et al. 2007), with coeval emplacement of granitic complexes and veins in the Lufilian Belt and adjacent areas (Hanson et al. 1993; Torrealday et al. 2000). Youngest reported events are indicated by intrusions of nepheline-syenite and diorite-granodiorite in the Domes Region of the Lufilian Belt, which yielded ages between 458 and 419 Ma (Cosi et al. 1992; Lobo-Guerrero Sanz 2005). Several occurrences of Palaeoproterozoic basement are known, of which the oldest reported zircons yielded ages at 2,072 ± 9 Ma (Rainaud et al. 2003, 2005). Detrital zircon record dates back to Mesoarchaean (3,225 ± 11 Ma) and shows further grains of Archaean and Palaeoproterozoic ages (Fig. 2; Rainaud et al. 2003; Master et al. 2005).

The NE-trending Irumide Belt is located E to the Lufilian Belt and corresponds to the southern metacratonic margin of the Bangweulu Block (Liégeois et al. 2013; Fig. 1). Thus it is not situated within the catchment areas of the sampled rivers. Nevertheless it could be a potential source region for detrital zircons. This belt is supposed to be directly situated at the southern margin of the Congo Craton (De Waele et al. 2008) and is mainly composed of Mesoproterozoic rocks (De Waele et al. 2006a, b; Frimmel et al. 2011). The youngest reported zircon age is 554 ± 20 Ma, followed by few magmatic events of about 943 to 946 Ma (De Waele et al. 2006b). Several major granitic intrusions occur between 1001 and 1055 Ma, while the ages around 1.02 Ga are assumed to be associated to the Rodinia assembly (De Waele et al. 2006b; Johnson and Rivers 2004; Liégeois et al. 2013). Several alkaline granite gneisses yield zircon age populations from ~1550 to 1665 Ma and are interpreted as melts from an Archaean source (De Waele et al. 2008; Liégeois et al. 2013). They intruded into the sedimentary succession of the Muva Supergroup (Liégeois et al. 2013 and references therein). Prior to the onset of this sedimentation, zircon data revealed at least two episodes of magmatic intrusions from 1856 to 1952 Ma and between 2029 and 2050 Ma (De Waele et al. 2006b; Rainaud et al. 2003, 2005). Only few zircon data older than Orosirian are reported (Rainaud et al. 2005; Fig. 2), with the oldest intrusion at 2726 ± 36 Ma (De Waele et al. 2006b) and the oldest detrital zircon at 3180 Ma found in the Muva Supergroup (Rainaud et al. 2005).

The Kalahari Basin

Most of the working area lies in the northern part of the Kalahari Basin, which is covered by Late Cretaceous to Cenozoic terrigenous sediments with maximum thicknesses around 450 m (Haddon and McCarthy 2005; Wanke and Wanke 2007). They are mainly composed of conglomerates, gravels, clays, sandstones and unconsolidated sands, mostly overlying sediments of the Karoo

Supergroup (Catuneanu et al. 2005), but also rocks of all pre-Karoo ages. Haddon and McCarthy (2005) suggest a south-eastward direction of the drainage since Upper Cretaceous times as did Goudie (2005), which has not changed yet, except for the Kunene River which was captured by the precursor of the lower Kunene during the Cenozoic (Miller 1997; Thomas and Shaw 1990), and now flows into the Atlantic Ocean. Thus, main direction of sedimentary transport processes in the rivers is from north-west to south-east. Continuous sedimentation from the Angolan hinterland is also deduced by Huntsman-Mapila et al. (2005) for the Okavango Basin and Miller (1997) for the Etosha Pan. Both authors also found signs of some aeolian input from reworked dunes of the adjacent Kalahari. There are two theories for the origin of the unconsolidated sand in the Kalahari Basin: weathering of in situ sandstones and transport of the material (Haddon 2005). Both processes are assumed to occur in coexistence. Thus, it has to be assumed that the sands may show influences from outside the working area.

Cretaceous to Tertiary intrusive complexes and Kimberlites

Several igneous complexes (Brandberg, Erongo, Kalkfeld, Okoruso, etc.) of early Cretaceous age occur in the Damara Belt. They are interpreted to be related to the opening of the South Atlantic Ocean (Schmitt et al. 2000; Wigand et al. 2004). Tertiary events are indicated by some phonolithic and nephelinitic intrusions in the Damaraland and Auas provinces (Pirajno 1994; Reid et al. 1990).

Kimberlitic intrusions occur sporadically throughout the working area and its adjacent regions (Batumike et al. 2008; Robles-Cruz et al. 2012). They reflect the youngest known magmatic events in southern Central Africa, displaying ages around 32, 60–70, 80–90, 110–121, 134–145, 216–252 and 372 Ma (Batumike et al. 2008, 2009; Haggerty et al. 1983; Nikitina et al. 2012; Robles-Cruz et al. 2012; and references therein).

Methods

A total of five samples of recent fluvial sediments from four major rivers of the southern Congo Craton were selected in order to determine morphology and U–Pb ages of zircons. Prior to isotopic analyses via LA–ICP–MS, morphology of each zircon grain and its crystal faces were studied utilising SEM to gain information about the approximate distance of transport and the melt composition during crystal growth (Pupin 1980).

For a detailed description of sample preparation, morphological studies, U–Pb dating and Th–U measurement, please refer to paragraphs 3.1 to 3.2 in the electronic supplement to this paper. Instrument setup details are provided in supplementary Table 1. All supplementary data are available from the journal website.

Results

The five samples contained 2,046 zircon grains, all of which were analysed with respect to their grain surface and crystal morphologies. Of them, 1,224 were definable according to the morphotypes of Pupin (1980). U–Pb measurements were executed on 1,317 zircons. In total, 614 analyses yielded ages with a concordance between 90 and 110 %, which were utilised for interpretative purposes. These grains are plotted in binned frequency and probability density distribution plots (Fig. 3) to facilitate the visualisation of primary magmatic and metamorphic events in the source areas of the sediments. The isotopic zircon grain measurements gathered with the aid of LA–ICP–MS and all data concerning the morphology are given in supplementary Tables 2 to 11 (available from the journal website). Below, the order of the samples is from west to east.

NAM-O-23, recent river sand, Kunene River, S17°25′50.6″, E14°07′09.9″

A total of 404 zircons of sample NAM-O-23 were studied. They are between 40 and 258 μm in length (mean 117 μm) and 22–130 μm in width (mean 61 μm). Most of the grains are subrounded to rounded, equal to classes 6 to 8 according to Gärtner et al. (2013). Of all grains, 239 can be classified in the diagram of Pupin (1980). Almost 30 % of the zircons show S23 to S25 morphology. Subpopulations are grouped around S7 and P1 including 22.6 and 11.3 % of the identifiable zircons (Fig. 4; Tab 2). Internal texture is mostly magmatic, and circa half of these grains exhibit late to postmagmatic recrystallisation or convolute zoning in the sense of Corfu et al. (2003). The rest shows clearly metamorphic overprint from sector and fir tree zoning to total homogenisation. One hundred and twenty-six of the 270 zircon grains analysed for age determination display concordant ages ranging between 1,066 ± 44 and 2,583 ± 20 Ma. Major peaks cluster around 1,379, 1,442, 1,736, 1,778, 1,861 and 1,964 Ma (Fig. 3; Tab 7). A characteristic gap in the age distribution pattern is between ~2,050 and ~2,570 Ma, with only one grain occurring in between.

NAM-O-25, recent river sand, Okavango River (NE), S17°23′27.9″, E18°25′14.9″

From sample NAM-O-25, 423 zircon grains were analysed. The length ranges from 39 to 301 μm (mean 99 μm) and width from 10 to 124 μm (mean 47 μm). Most of the

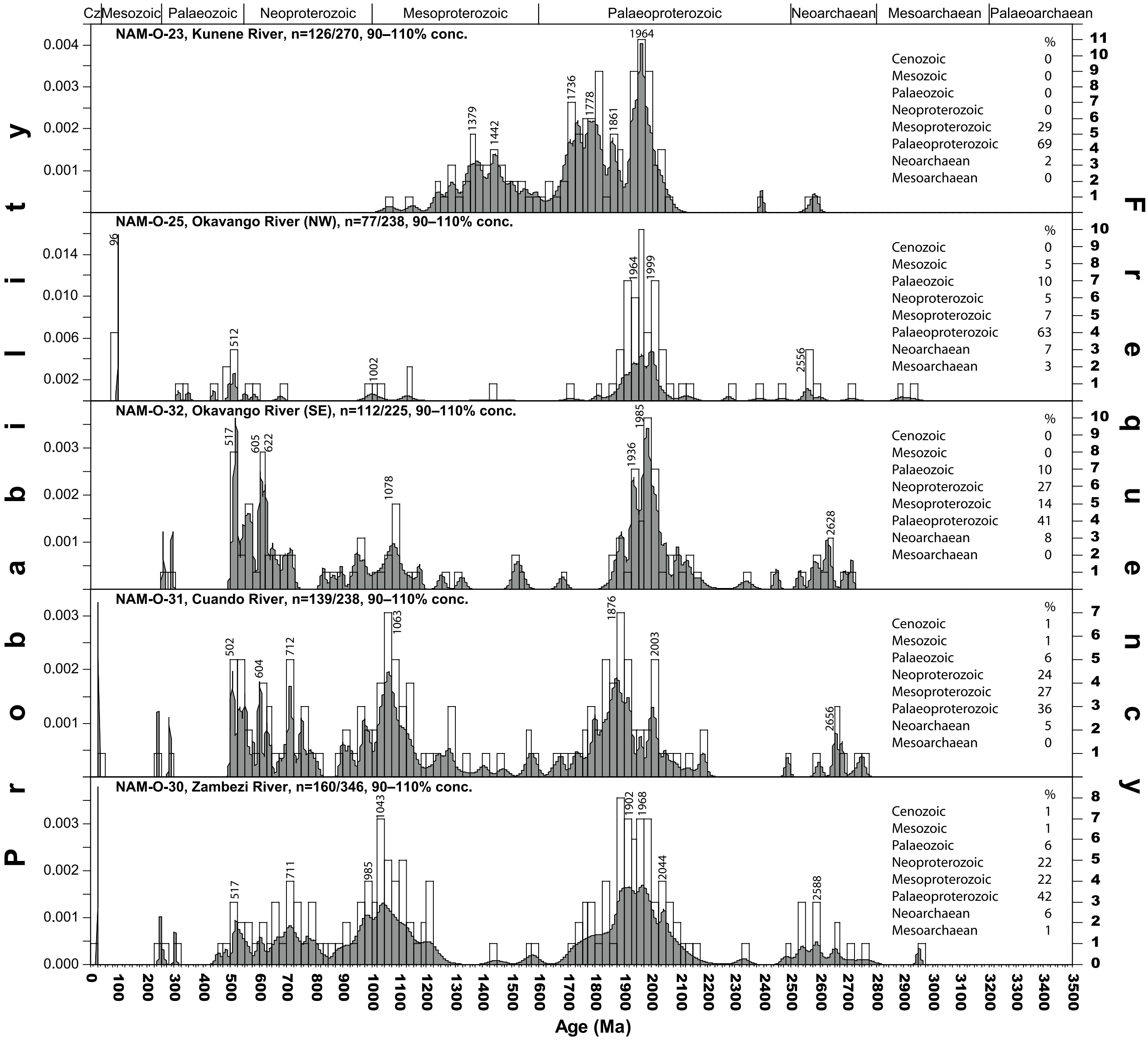

Fig. 3 Binned probability density plots of all zircons measured for U–Pb age determination yielding concordance levels of between 90 and 110 %, including calculated mean ages of major peaks

zircons are subrounded with a main peak between classes 5 and 7 (Gärtner et al. 2013). Of all grains, 309 are distinguishable within the diagram of Pupin (1980). There is no major concentration of morphotypes, but minor focal points are around S7 (22.0 %) and S24 (31.7 %; Fig. 4; Tab 3). About two-thirds of all grains show concentric zoning, a typical internal texture pointing to magmatic origin. But half of them exhibit characteristics of late- to postmagmatic influences (Corfu et al. 2003). The remaining grains display metamorphic overprint of all stages. Roughly one-third (77) of the 238 zircons analysed for U–Pb values yield concordant ages. They range between 96 ± 2 and 2,929 ± 42 Ma with distinct peaks at 96, 512, 1,002, 1,964, 1,999 and 2,556 Ma (Fig. 3; Tab 8). Around 5 % of all concordant grains are of Mesozoic age. A large gap in the age distribution pattern can be found between 1,136 Ma and 1,712 Ma, with only one grain, itself displaying a large error, occurring in between.

NAM-O-32, recent river sand, Okavango River (SE), S18°06′22.2″, E21°37′01.8″

Of sample NAM-O-32, a total of 442 zircon grains were analysed with respect to their morphological characteristics. They are between 38 and 231 µm in length (mean 119 µm) and 21–118 µm in width (mean 57 µm). The

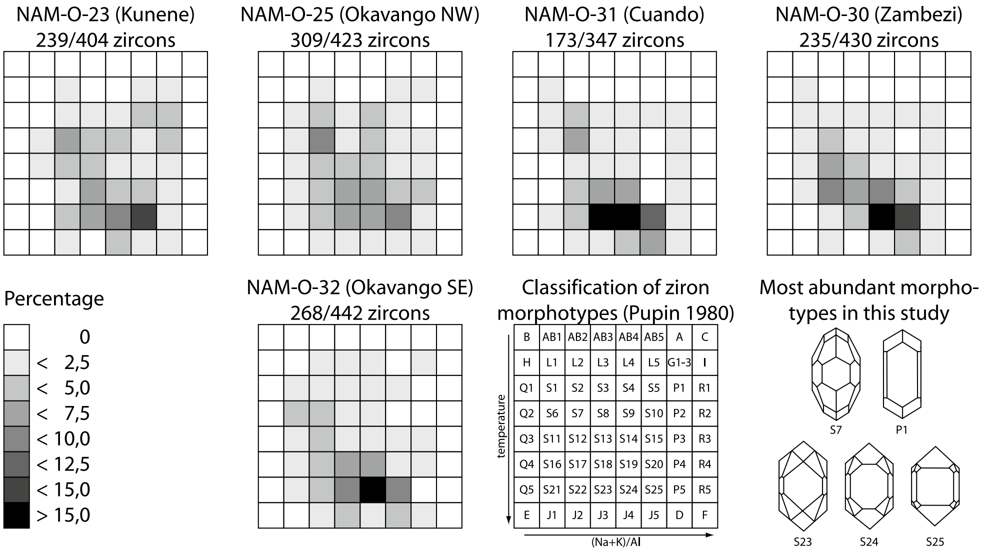

Fig. 4 Distribution patterns of the zircon morphotypes according to Pupin (1980) for all samples presented in this paper

majority of all grains are subrounded to rounded, equal to classes 5–7 according to Gärtner et al. (2013). Of them, 268 can be classified using the diagram of morphotypes introduced by Pupin (1980). Only one dominant cluster occurs around morphotype S24 comprising 62.3 % of the identifiable grains (Fig. 4; Tab 4). More than 60 % of the zircons display internal textures related to magmatic origin, but half of them show indication of late- to postmagmatic influence (Corfu et al. 2003). The remaining grains exhibit metamorphic overprint of all stages. A total of 225 grains were dated by U–Pb isotopes, with 112 zircons yielding concordant ages between 259 ± 6 and 2,713 ± 12 Ma. Main peaks are at 517, 605, 622, 1,078, 1,936, 1,985 and 2,628 Ma (Fig. 3; Tab 9). Few grains occur between 1,137 and 1,860 Ma, mostly displaying ages at about 1,525 Ma. Another gap in the age distribution pattern is between 2,167 and 2,529 Ma.

NAM-O-31, recent river sand, Cuando River, S17°51′19.9″, E23°21′41.6″

Sample NAM-O-31 contained 347 zircon grains, showing lengths between 50 and 264 μm (mean 111 μm) and widths of 22–123 μm (mean 59 μm). The majority of grains are rounded, according to classes 6–8 of Gärtner et al. (2013). Of all grains, 173 are definable according to Pupin (1980), mostly clustering around S23 and S24 morphotypes (53.8 %). A minor concentration is characterised by the S7 and adjacent types (16.8 %; Fig. 4; Tab 5). Zircons of this sample largely show internal textures related to magmatic growth (Corfu et al. 2003). More than half of them display some late- to postmagmatic growth characteristics. Roughly one-third of all zircon grains indicate metamorphic overprint. U–Pb measurements of 238 zircons yield 139 ages between 29 ± 2 and 2,752 ± 19 Ma within 90–110 % concordance. Main peaks can be found at 506, 604, 712, 1,063, 1,876, 2,003 and 2,656 Ma (Fig. 3; Tab 10). A significant gap occurs between 2,185 and 2,598 Ma.

NAM-O-30, recent river sand, Zambezi River, S17°29′35.4″, E24°16′11.3″

Of this sample 430 zircon grains were analysed. The values for lengths range from 36 to 232 μm (mean 99 μm) and for widths from 19 to 107 μm (mean 53 μm). Most of the grains are subrounded to rounded, equal to classes 5–7 according to Gärtner et al. (2013). About the half of all grains have internal textures related to magmatic crystal growth, but most of them with characteristics related to late- or postmagmatic influences (Corfu et al. 2003). The other half displays metamorphic overprints of all stages. Altogether, 235 of 430 zircons could be classified according to Pupin (1980). A major concentration of morphotypes is grouped around S24 and S25 (57.3 %). Generally, the distribution pattern is very similar to sample NAM-O-31 (Fig. 4; Tab 6). Of 346 zircons measured for U–Pb age determination, 160 are concordant within 90–110 % and yield ages between 23 ± 1 and 2,953 ± 14 Ma. The main peaks are at 517, 711, 985, 1,043, 1,902, 1,968, 2,044 and 2,588 Ma (Fig. 3; Tab 11). A characteristic gap in the age distribution pattern occurs between 1,222 and 1,711 Ma, and a second one ranges from 2,153 to 2,535 Ma, both with only few grains in between.

Discussion

The zircon data of this study can be used for two issues: (a) the provenance of recent sediments in this part of the Kalahari Basin and (b) the reconstruction of episodic growth and reworking of the continental crust at the southern margin of the Congo Craton. The sizes of the catchment areas are equal to the landmass area that was sampled. This area comprises approximately 764,000 km^2 (Fig. 1), which is equivalent to ca. 13 % of the total area of the Congo Craton (~5,800,000 km^2, estimated following the model of Congo Craton extent by Hanson 2003; De Waele et al. 2008).

The drainage pattern in the working area is supposed to have been directed to the SE since at least Cretaceous times (Goudie 2005). This is possibly related to the doming of the Paraná plume (Moore and Blenkinsop 2002; Jackson et al. 2005). An exception is the Kunene River which was captured in Cenozoic but first terminated into Etosha Pan (Goudie 2005; Buch and Rose 1996; Haddon and McCarthy 2005; Thomas and Shaw 1990). Reconstructions for the wind systems in the working area prior to Pliocene are not available. For the Quaternary, it is assumed that the Southern Hemisphere trade wind system was the main factor of aeolian sediment transport parallel to the western coast of southern Africa (Maslin et al. 2012). Nevertheless, fluctuations concerning the wind intensity have been supposed by Shi et al. (2001). Around the working area, there is a large air current, normally rotating in clockwise direction (Pichevin et al. 2005; Krueger et al. 2008). Thus, a mixture of aeolian components is theoretically possible. Reported average grain size of aeolian sediments from different places around the world ranges between 250 and 17 μm (e.g. El-Sayed 1999; Wang et al. 2003), while the average for world aeolian sands is ca. 200 μm (Goudie et al. 1987; $\rho \approx 2.7$ g cm^{-1}). Caused by the higher density of zircon (4.6–4.7 g cm^{-1}), the average size of aeolian zircon grains is suggested to be significantly smaller. Hence, an aeolian transport is only possible for a very limited amount of the sampled zircon grains. As a consequence, the influence of aeolian zircon components is assumed to be very low. Both the drainage pattern and the wind system hypothesise a major influence of the Angola Block for the Kunene and Okavango River systems, for the latter one at least until sample location NAM-O-25.

Provenance of the sediments

Most of the zircons from the recent Kunene River (NAM-O-23) display ages between 1,200 and 2,100 Ma. Major peaks at 1,379 and 1,442 Ma are in agreement with the already known data from the southern parts of the Kunene Intrusive Complex (Drüppel et al. 2000, 2007; Mayer et al. 2004), but can also be derived from the Angola Block and its overlying sediments (De Carvalho et al. 2000; Pereira et al. 2011). The majority of these zircons belong to the morphotypes S20, S24 and S25 (Tab. 2), pointing to high temperatures and subalkaline to alkaline conditions during zircon formation (Pupin 1980; Pupin and Persoz 1999). Such kinds of rocks occur in the southern Kunene Intrusive Complex (De Carvalho 1974; Pereira et al. 2011). The peaks between 1.8 and 1.7 Ga are highly likely caused by zircons derived from the Epupa Metamorphic Complex, the Epembe unit, the Angola Block itself or possibly undated equivalents within the catchment area (Kröner et al. 2010; Rapela et al. 2011; Seth et al. 2003). They display mostly S12, S13, S18, S19 and S22 to S24 morphotypes (Tab. 2), indicating aluminous to subalkaline rocks (Pupin 1980). Both age populations mentioned above are characteristic of the catchment area of the Kunene River and do not occur in increased abundance within the other samples or catchment areas (Figs. 1, 2, 3). A minor peak at 1,861 Ma could represent zircons from the Epupa Metamorphic Complex, which is adjacent to the sampling locality. Reported ages of this complex are in accordance with the obtained ages in this study (Kröner et al. 2010). The distinct peak around 1,964 Ma is in accordance with the ages reported from the Angola Block (McCourt et al. 2004) and the overlying Chela Group (Pedreira and De Waele 2008; Pereira et al. 2011). Most of the zircon morphotypes are related to alkaline and subalkaline melt conditions (Pupin 1980; P1–P5, S10, S18–20, S23–25). The oldest grains of ca. 2.58 Ga are quite likely from the Angola Block (De Carvalho et al. 2000; Rapela et al. 2011).

Although there are some west winds (Pichevin et al. 2005; Krueger et al. 2008), sample NAM-O-25 (Okavango River) did not contain any zircons with ages typical for the Kunene Intrusive or Epupa Metamorphic Complex. This is interpreted as evidence for the low influence of aeolian components. Youngest zircons yielded ages about 96 Ma and morphotypes related to high temperatures and alkaline conditions (Pupin 1980). They are almost not rounded and have grain sizes noticeably larger than the mean. Because of these characteristics, the grains are possibly derived from nearby kimberlites (Robles-Cruz et al. 2012). All zircons with ages around 0.6–0.5 Ga are supposed to be related to the Pan-African orogeny, which likely affected the adjacent Damara Belt between 0.58 and 0.5 Ga (Gray et al. 2006; Schmitt et al. 2012). Few grains yielded ages at about 1.0 Ga, which are exotic for this region and yet are only known as rare detritus from the Damara Belt (McGee et al. 2012). Potential source regions are the Rehoboth area (Becker et al. 2006; McGee et al. 2012), and, more likely, the Kibaran Belt (Kokonyangi et al. 2006) or NW Botswana (Kampunzu et al. 2000). Most of them are rounded to completely rounded, which is suggested to indicate a long distance of transport (Dietz 1973; Gärtner 2011; Gärtner et al. 2013). As there are no Palaeoproterozoic zircons from the Epupa Metamorphic and Kunene Intrusive Complexes, the source area of the population between 2.0 and 1.9 Ga has to be searched elsewhere. They can be divided into two groups of morphotypes, which are related to more aluminous (S2, S4, S8, S18) and subalkaline to alkaline (P1, P4, S10, S15, S20, S23–S25, J4) melt compositions (Pupin 1980). Further zircons of Orosirian age are known from the Angola Block (McCourt et al. 2004; Rapela et al. 2011), but also from sediments and basement inliers of the Damara (McGee et al. 2012) and Lufilian Belts (Ngoyi et al. 1991; Rainaud et al. 2003, 2005), of which the latter two are interpreted as the preferable source areas. The oldest grains of this sample may originate from Siderian to Neoarchaean igneous and metamorphic units of the eastern Angola Block (De Carvalho et al. 2000), which are drained by the upper reaches of the Cubango–Okavango system (Fig. 1).

Due to very similar morphotype and age distribution patterns (Figs. 3, 4), the samples NAM-O-32, 31 and 30 from the recent Okavango, Cuando and Zambezi Rivers are discussed in the same paragraph. The early Cretaceous anorogenic complexes (Schmitt et al. 2000; Wigand et al. 2004), the Eocene phonolites and nephelinites (Reid et al. 1990), as well as kimberlitic and carbonatitic intrusions are the only known magmatic events until ~400 Ma in the whole working area and its adjacent regions (Batumike et al. 2008, 2009; Haggerty et al. 1983; Nikitina et al. 2012; Robles-Cruz et al. 2012). Hence, all zircons up to that age are interpreted as related to these intrusions, while especially the Triassic rocks are located in the central northern parts of the working area (Fig. 1). Any influence of the early Cretaceous magmatites of the Damara Belt can be excluded according to the lack of such zircon ages (Fig. 3). The two youngest grains of Oligocene age are only poorly rounded and display morphotypes related to high temperatures and alkaline conditions (J4, J5; Pupin 1980). The remaining grains of this group have morphotypes of subalkaline character and form two minor peaks at about 250–260 and 290–300 Ma (Fig. 3). Two zircons with pre-kimberlitic and post-Pan-African ages at 456 ± 20 and 483 ± 16 Ma occur only in the Zambezi sands (NAM-O-30). They can possibly be linked to intrusions of nepheline-syenite and diorite-granodiorite in the Domes Region of the Lufilian Belt (Cosi et al. 1992; Lobo-Guerrero Sanz 2005). Ages between 0.65 and 0.5 Ga are supposed to be related to the Pan-African orogeny. They occur in the Damara and the Lufilian Belt as well (Gray et al. 2006; Schmitt et al. 2012; Cosi et al. 1992; Key and Armstrong 2000; Porada and Berhorst 2000; Batumike et al. 2007). The amount of zircon grains with ages 0.8–0.7 Ga increases to the east. These ages are typical for the extensional magmatism in the course of the break-up of Rodinia and occur at several locations in the Lufilian Belt (Key et al. 2001; Johnson and Rivers 2004; Ernst et al. 2008; Wendorff and Key 2009). They are also known from the Damara Belt (Hoffman et al. 1996; Hanson 2003; Halverson et al. 2005; Jung et al. 2007; Frimmel and Miller 2009; McGee et al. 2012), but could not be found in the westernmost sample (NAM-O-32), which is linked to this orogen by the Omatako River (Fig. 1). Thus, we interpret zircons of this age to be derived mainly from the Lufilian Belt. Zircons forming the significant peaks between 1.2 and 0.9 Ga are assumed not to be derived from the Damara and Lufilian Belts where they are only reported as detritus (Fig. 2; McGee et al. 2012; Rainaud et al. 2005). However, several Tonian–Stenian intrusions are known from the Kibaran (Kokonyangi et al. 2004, 2006) and Irumide Belts (Johnson and Rivers 2004; De Waele et al. 2006a, b; Frimmel et al. 2011) as well as the Choma Kalomo Block (De Waele et al. 2006b). These regions are interpreted as the potential source areas for zircons of this population. Most of the grains show characteristics of the morphotypes S18, S19, S23–S25, J5, P4 and P5 (Tab 4 to 6), which are supposed to be related to subalkaline to alkaline melt conditions (Pupin 1980). Therefore, a further classification based on age and morphotype is not possible. One hint to different source areas of the Tonian–Stenian grains is given by the roundness of the zircons, which led to two populations in the samples NAM-O-30 and NAM-O-31 (Tab 5 and 6). Some grains of both samples are poorly rounded and are possibly derived from the near Choma Kalomo Block, but the majority of all grains are rounded to completely rounded and seem to originate from more distant areas (Dietz 1973; Gärtner 2011; Gärtner et al. 2013). In sample NAM-O-32, all grains of this population are more or less equal rounded (Tab 4). A characteristic gap in the zircon age distribution pattern occurs between ca. 1.7 and 1.27 Ga (Fig. 3). A major peak in all three samples is situated between ~2.1 and ~1.7 Ga. These ages occur only in few basement inliers or sedimentary rocks in the Damara Belt (Kisters et al. 2004; McGee et al. 2012) and are also rare in the Kibaran Belt (Tack et al. 2010). But they are known from a large number of igneous rocks of the Lufilian Belt (Key et al. 2001; Rainaud et al. 2003, 2005; Lobo-Guerrero Sanz 2005; Master et al. 2005) and rarely from the Kasai Block (Key et al. 2001). In all cases, zircons of this age group are consistent with the fields displaying the highest percentage of morphotypes within the diagram of Pupin (1980; Fig. 4). The oldest grains of the samples NAM-O-30, 31 and 32 yielded ages from 2.95 to 2.5 Ga, which are only known, and therefore interpreted to be linked to the Kasai Block (De Carvalho et al. 2000; Key et al. 2001; Rainaud et al. 2005; De Waele et al. 2008; Batumike et al. 2009). Due to the small amount of zircons older than 2.6 Ga and the total absence of zircons older than 3.0 Ga, a provenance deduced from the Zimbabwe Craton is highly unlikely.

Summarising the suggested provenances of all measured zircon age populations, the major part of the sediments that cover the northern Kalahari Basin may be derived from currently elevated areas such as the Kasai

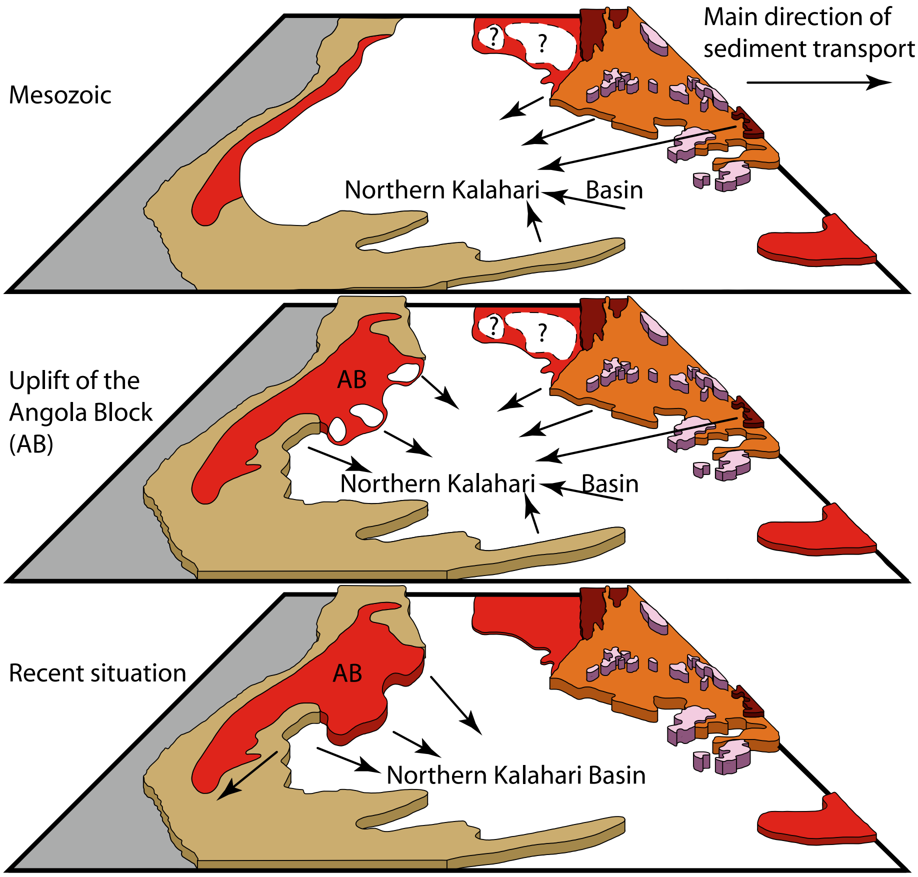

Fig. 5 Schematic model for the main directions of sediment transport prior to the uplift of the Angola block, just after its uplift, and to date. For further information see Figs. 1 and 2

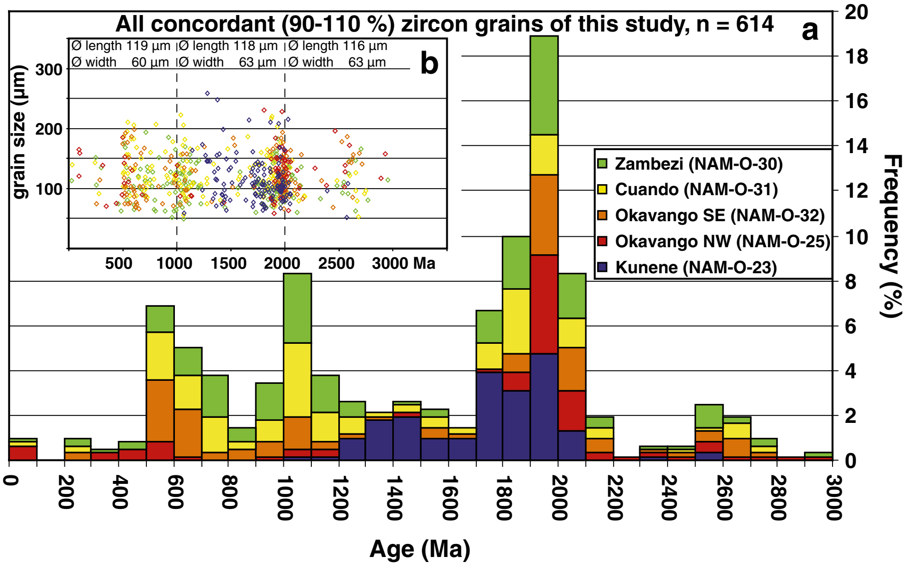

Fig. 6 **a** Binned frequency plot of all concordant (90–110 %) zircon grains of this study (bin width = 100 Ma), illustrating episodic zircon formation discussed in this article. **b** U–Pb ages of all concordant zircons plotted against their grain size, indicating no significant correlation between both characteristics

Block, the E Lufilian and the SE to S Damara Belts (whose influence increases to the west). Smaller portions from the NE Kibaran Belt are also conceivable. The possible influence of the Angola Block and the Epupa Metamorphic and Kunene Intrusive Complexes could only be detected within the catchment area of the Kunene River and is assumed for small parts of the upper reaches of the Cubango–Okavango Rivers. Taking into consideration the weak detectable impact of the Angola Block within the sediments, the existence of a sedimentary cover of large western extent has to be suggested prior to Mesozoic and Tertiary uplift caused by the postulated emplacement of the Paraná superplume (Moore and Blenkinsop 2002) and several subsequent tectonic events (Jackson et al. 2005). Jackson et al. (2005) also mention that estimates concerning time and extent of the uplift vary enormously. In the course of the uplift, the Angola Block is now weathered again due to complete erosion of the hypothesised meantime sedimentary cover. This process is still ongoing and will provide zircons of the Angola Block for future sediments (Fig. 1, note the upper reaches of the Cubango–Okavango Rivers, Fig. 5). Additionally, it has to be mentioned that there is no certainty about the number of recycling and reworking cycles within the Cenozoic sediments of the northern Kalahari Basin.

Growth history of the southern margin of the Congo Craton

The combination of all concordant zircon ages of this study led to Fig. 6a, showing the frequency distribution pattern of zircon ages for the whole working area. There are four dominant peaks at 2.7–2.5, 2.1–1.7, 1.2–0.9 and 0.8–0.5 Ga, while the 2.1–1.7 Ga peak is the largest throughout the entire working area (Fig. 3). The distribution of the peaks is in accordance with the reported global record (Condie 2000; Campbell and Allen 2008; Rino et al. 2008; Belousova et al. 2010; Condie and Aster 2010). Remarkably, the age distribution pattern is also very similar to that reported from the mouth of the Congo River, while the data from the mouth of the Zambezi River are dominated by a ca. 1.0 Ga peak (Rino et al. 2008), possibly resulting from major input of the Irumide Belt (Johnson and Rivers 2004; De Waele et al. 2006a, b; Frimmel et al. 2011). The peaks are interpreted to reflect the main zircon-forming events during time at the southern margin of the Congo Craton. Unlike it is suggested by Rino et al. (2008), there is no necessity to link all episodic events to the growth of continental crust. Several studies of Sm–Nd, Lu–Hf and oxygen isotopes from zircons showed that most parts of the continental crust were likely separated from mantle during Archaean and were mostly reworked during later orogenies (De Waele et al. 2006b; Wang et al. 2009; Belousova et al. 2010; Condie and Aster 2010; Lancaster et al. 2011). Furthermore, it is supposed that generation of juvenile crust decreased during time (Belousova et al. 2010; Condie and Aster 2010). There are suggestions that the highest amount of new juvenile crust is produced in continental accretionary orogens (Condie and Kröner 2013). Nevertheless, the question concerning the growth rates of continental crust is still under discussion, which is illustrated by the many existing models (summarised in Rino et al. 2004; Belousova et al. 2010; Bradley 2011).

There is agreement that the cyclicity most possibly is linked to the supercontinental cycle (e.g. Rino et al. 2008; Belousova et al. 2010; Condie and Aster 2010; Lancaster et al. 2011). The major amount of zircons is supposed to be formed during the dispersion of a supercontinent and the amalgamation of its successor (Bradley 2011). In the case of this study, signs for four of these events could be detected due to significant clustering of zircon ages. The hypothesised Vaalbara continent potentially broke up at about 2.7–2.5 Ga (Bleeker 2003; Barely et al. 2005), which might reflect the 2.7–2.5 Ga peak (Fig. 6a). The next episode is assumed to be represented by the dispersion of several proposed Archaean continents between 2.1 and 1.9 Ga, and the subsequent formation of Nuna from ca. 1.8 to ca. 1.6 Ga (Rino et al. 2008; Bradley 2011; Lancaster et al. 2011; Meert 2012). In this study, the majority of all zircons yielded ages between 2.1 and 1.7 Ga. Thus, they represent potential relicts of these events, which may have had a strong impact on the basement rocks of almost the entire working area (Fig. 2). The global zircon record (Condie 2000; Campbell and Allen 2008; Rino et al. 2008; Belousova et al. 2010; Condie and Aster 2010) and the data of this study (Fig. 6a) show a break within the relatively low production rate of Mesoproterozoic zircons around 1.3 Ga. This is possibly linked to the hypothesised break-up of Nuna and the assemblage of Rodinia at about 1.3–1.1 Ga (Torsvik 2003; Ernst et al. 2008; Evans 2009) accompanied by the Kibaran orogeny (Fig. 2; Rainaud et al. 2005; Kokonyangi et al. 2006; Tack et al. 2010). Break-up of Rodinia and amalgamation of Gondwana at about 0.85 to 0.55 Ga (Torsvik 2003; Li et al. 2008; Evans 2009) are most likely the major zircon-producing events that are preserved in the 0.8–0.5 Ga peak. In the working area, only the Damara, Kaoko and Lufilian Belts, all at the southern margin of the Congo Craton (Figs. 1, 2), seem to have been affected by both events, which are supposed to have overlapped in time (Rino et al. 2008; Bradley 2011). All younger zircon grains are interpreted as related to kimberlitic, nephelinitic or phonolithic intrusions, because it is assumed that there were no active margins existing at this region during the Pangaea assemblage (chapter 5.1; Bradley 2011). Taking into account these considerations, the southern margin of the Congo Craton was recurrently destabilised at ~2.7, 1.9, 1.0 and 0.6 Ga. In general, this is quite similar to the model for the Irumide Belt published by De Waele et al. (2006b).

Hydrodynamic fractionation of zircon age populations and connections between age and morphotype

Besides the main objectives of this study, measurements of zircon age and grain size did not reveal any relation between both features (Fig. 6b). This is not in accordance with the hypothesised hydrodynamic fractionation of

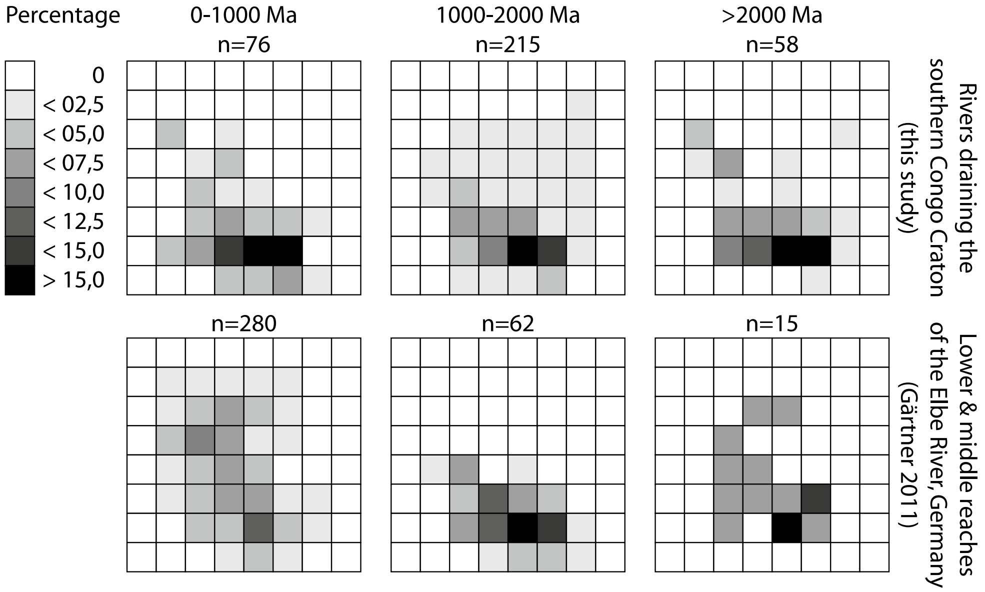

Fig. 7 Distribution patterns of zircon morphotypes of different age populations from southern Congo Craton compared to central to northern Germany (with supposed Baltica influence). The morphotypes indicate high temperatures caused by thick cratonic crust during zircon crystallisation in the first case and low temperatures due to thinner crust in the second

zircon age populations by Lawrence et al. (2011) and Yang et al. (2012).

Most of the concordant zircons of this study show morphotypes that are typical for high temperatures during crystal growth according to Pupin (1980). Unlike other areas, e.g. northern central Europe, they do not show significant variations of morphotypes plotted against age (Gärtner 2011; Fig. 7). Because the continental crustal and lithosphere thicknesses are supposed to have been higher in Archaean to Mesoproterozoic than in later times (Durrheim and Mooney 1994; Artemieva and Mooney 2001), it is suggested that increased heat production led to zircon morphotypes that indicate high temperatures. In case of the southern Congo Craton, the data support the assumption for most of the zircons with ages younger than Mesoproterozoic (Fig. 7).

Conclusions

The obtained zircon data help to identify possible provenance for the recent to Cenozoic sediments of the northern Kalahari Basin, an issue that has been under discussion for long time (Haddon 2005 and references therein). Zircon age distribution patterns led to the assumption that the sediments were mainly derived from the eastern Lufilian Belt and show minor input from the Kibaran as well as the Irumide Belts. An increasing influence of the Damara Belt as a source for sediments to the west has to be suggested. Notwithstanding the SE-trending drainage pattern, which is inferred to have been onset in Cretaceous times (Goudie 2005; Haddon and McCarthy 2005), the influence of sediments with typical characteristics of the Angola Block is most likely limited to the catchment area of the Kunene und uppermost Cuando–Okavango Rivers. According to this, it is supposed that there was a sedimentary cover of E to S provenance which possibly extended further west prior to the uplift of the Angola Block caused by assumed Mesozoic superplume emplacement (Moore and Blenkinsop 2002) and subsequent Tertiary tectonic events (Jackson et al. 2005). Since the Mesozoic uplift, the main direction of sediment transport is supposed to be NW–SE, resulting in the exhumation of the Angola Block.

Analyses of the sediments also suggest a recurrent destabilisation of the southern margin of the Congo Craton at ~2.7, 1.9, 1.0 and 0.6 Ga, represented by major peaks in the age distribution pattern of the total amount of concordant zircons. This is in accordance with similar studies in adjacent areas (De Waele et al. 2006b). Furthermore, the obtained data fit well to several hypothesised major events during the supercontinent cycle (Rino et al. 2008; Belousova et al. 2010; Bradley 2011).

The studied zircons do not show any correlation between age and grain size and therefore do not support the model of hydrodynamic fractionation of zircon age populations (Lawrence et al. 2011; Yang et al. 2012). Most of the obtained crystal morphotypes, especially of the concordant zircon grains, are related to high temperatures during crystal growth (Pupin 1980). This is suggested reflecting the influence of a thick ancient continental crust and the underneath heat accumulation.

Acknowledgments J-P Liégeois and A Wanke are thanked for their constructive and critical reviews in order to improve the manuscript. The authors are very grateful to C Quesada for his help and patience during the entire publishing process.

References

Alkmim FF, Martins-Neto MA (2012) Proterozoic first-order sedimentary sequences of the São Francisco craton, eastern Brazil. Mar Petrol Geol 33:127–139

Armstrong RA, Master S, Robb LJ (2005) Geochronology of the Nchanga Granite, and constraints on the maximum age of the Katanga Supergroup, Zambian Copperbelt. J Afr Earth Sci 42:32–40

Artemieva IM, Mooney WD (2001) Thermal thickness and evolution of Precambrian lithosphere: a global study. J Geophys Res 106:16387–16414

Barely ME, Bekker A, Krapež B (2005) Late Archean to early Paleoproterozoic global tectonics, environmental change and the rise of atmospheric oxygen. Earth Planet Sci Lett 238:156–171

Batumike MJ, Cailteux JLH, Kampunzu AB (2007) Lithostratigraphy, basin development, base metal deposits, and regional correlations of the Neoproterozoic Nguba and Kundelungu rock successions, central African Copperbelt. Gondwana Res 11:432–447

Batumike JM, Griffin WL, Belousova EA, Pearson NJ, O'Reilly SY, Shee SR (2008) LAM–ICPMS U–Pb dating of kimberlitic perovskite: eocene–Oligocene kimberlites from the Kundelungu Plateau, D.R. Congo. Earth Planet Sci Lett 267:609–619

Batumike JM, Griffin WL, O'Reilly SY, Belousova EA, Pawlitschek M (2009) Crustal evolution in the central Congo–Kasai Craton, Luebo, D.R. Congo: insights from zircon U–Pb ages, Hf-isotope and trace-element data. Precambrian Res 170:107–115

Becker T, Schreiber U, Kampunzu AB, Armstrong R (2006) Mesoproterozoic rocks of Namibia and their plate tectonic setting. J Afr Earth Sci 46:112–140

Belousova EA, Kostitsyn YA, Griffin WL, Begg GC, O'Reilly SY, Pearson NJ (2010) The growth of the continental crust: constraints from zircon Hf-isotope data. Lithos 3–4:457–468

Binda PL, van Eden JG (1972) Sedimentological evidence on the origin of the Precambrian Great Conglomerate (Kundelungu Tillite), Zambia. Palaeogeogr Palaeoclimatol Palaeoecol 12:151–168

Bleeker W (2003) The late Archean record: a puzzle in ca. 35 pieces. Lithos 71:99–134

Bradley DC (2011) Secular trends in the geologic record and the supercontinent cycle. Earth Sci Rev 108:16–33

Brandt S, Will TM, Klemd R (2007) Magmatic loading in the Proterozoic Epupa Complex, NW Namibia, as evidenced by ultrahigh-temperature sapphirine bearing orthopyroxene-sillimanite-quartz granulites. Precambrian Res 153:143–178

Buch MW, Rose D (1996) Mineralogy and geochemistry of the sediments of the Etosha Pan Region in northern Namibia: a reconstruction of the depositional environment. J Afr Earth Sci 22(3):355–378

Cahen L, Snelling NJ, Delhal J, Vail JR, Bonhomme M, Ledent D (1984) The geochronology and evolution of Africa. Oxford University Press, Oxford

Cailteux JLH, Kampunzu AB, Lerouge C, Kaputo AK, Milesi JP (2005) Genesis of sediment-hosted stratiform copper-cobalt deposits, central African Copperbelt. J Afr Earth Sci 42:134–158

Campbell IH, Allen CM (2008) Formation of supercontinents linked to increases in atmospheric oxygen. Nat Geosci 1:554–558

Catuneanu O, Wopfner H, Eriksson PG, Cairncross B, Rubidge BS, Smith RMH, Hancox PJ (2005) The Karoo basins of south-central Africa. J Afr Earth Sci 43:211–253

Condie KC (2000) Episodic continental growth models: afterthoughts and extensions. Tectonophysics 322:153–162

Condie KC, Aster RC (2010) Episodic zircon age spectra of orogenic granitoids: the supercontinent connection and continental growth. Precambrian Res 180:227–236

Condie KC, Kröner A (2013) The building blocks of continental crust: evidence for a major change in the tectonic setting of continental growth at the end of the Archean. Gondwana Res 23:394–402

Corfu F, Hanchar JM, Hoskin PWO, Kinny P (2003) Atlas of zircon textures. In: Hanchar JM, Hoskin PWO (eds) Zircon. Rev Miner Geochem 53:468–500

Cosi M, De Bonis A, Gosso G, Hunziker J, Martinotti G, Moratto S, Robert JP, Ruhlman F (1992) Late Proterozoic thrust tectonics, high-pressure metamorphism and uranium mineralization in the Domes Area, Lufilian Arc, northwestern Zambia. Precambrian Res 58:215–240

De Carvalho H (1974) Geologia de Angola, 1:1.000.000, 4 sheets. Serviços de Geologia e Minas, Instituto de Investigação Científica. C^{a} Diamantes de Angola. Empresa de Cobre de Angola, C^{a} Mineira do Lobito, Petrangol, Angol e Cabinda Guff

De Carvalho H, Tassinari C, Alves PH, Guimarães F, Simões MC (2000) Geochronological review of the Precambrian in western Angola: links with Brazil. J Afr Earth Sci 31(2):383–402

De Waele B, Kampunzu AB, Mapani BSE, Tembo F (2006a) The Mesoproterozoic Irumide belt of Zambia. J Afr Earth Sci 46:36–70

De Waele B, Liégeois J-P, Nemchin AA, Tembo F (2006b) Isotopic and geochemical evidence of Proterozoic episodic crustal reworking within the irumide belt of south-central Africa, the southern metacratonic boundary of an Archaean Bangweulu Craton. Precambrian Res 148:225–256

De Waele B, Johnson SP, Pisarevsky SA (2008) Palaeoproterozoic to Neoproterozoic growth and evolution of the eastern Congo Craton: its role in the Rodinia Puzzle. Precambrian Res 160:127–141

Delor C, Theveniaut H, Pato D, Cage M (2007) Esboço litochronologico da República de Angola, a escala de 1:2.000.000. Ministério da Geologia e Minas, Instituto Geológico de Angola, Luanda

Dietz V (1973) Experiments on the influence of transport on shape and roundness of heavy minerals. Contrib Sedimentol 1:69–102

Drüppel K, Littmann S, Okrusch M (2000) Geo- und isotopenchemische Untersuchungen der Anorthosite des Kunene-Intrusiv-Komplexes (KIC) in NW-Namibia. Berichte der Deutschen Mineralogischen Gesellschaft. Eur J Miner 12(Suppl):37

Drüppel K, Littmann S, Romer RL, Okrusch M (2007) Petrology and isotope geochemistry of the Mesoproterozoic anorthosite and related rocks of the Kunene Intrusive Complex, NW Namibia. Precambrian Res 156:1–31

Durrheim RJ, Mooney WD (1994) Evolution of the Precambrian lithosphere: seismological and geochemical constraints. J Geophys Res 99:15359–15374

El-Sayed MI (1999) Sedimentological characteristics and morphology of the aeolian sand dunes in the eastern part of the UAE: a case study from Ar Rub' Al Khali. Sediment Geol 123:219–238

Ernst RE, Wingate MTD, Buchan KL, Li ZX (2008) Global record of 1600–700 Ma Large Igneous Provinces (LIPs): implications for the reconstruction of the proposed Nuna (Columbia) and Rodinia supercontinents. Precambrian Res 160:159–178

Evans DAD (2009) The palaeomagnetically viable, long-lived and all-inclusive Rodinia supercontinent reconstruction. Geol Soc Lond SP 327:371–404

Frimmel HE, Miller RM (2009) Continental rifting. Neoproterozoic to early Palaeozoic evolution of Southwestern Africa. In: Gaucher C, Sial AN, Halverson GP, Frimmel HE (eds) Neoproterozoic–Cambrian tectonics, global change and evolution: a focus on Southwestern Gondwana. Elsevier, Amsterdam. Dev Precambrian Geol 16:153–159

Frimmel HE, Basei MS, Gaucher C (2011) Neoproterozoic geodynamic evolution of SW-Gondwana: a southern African perspective. Int J Earth Sci (Geol Rundsch) 100:323–354

Gärtner A (2011) Morphologische, geochronologische und isotopengeochemische Untersuchungen an rezenten Sedimenten der Elbe. Unpublished diploma thesis, University of Dresden

Gärtner A, Linnemann U, Sagawe A, Hofmann M, Ullrich B, Kleber A (2013) Morphology of zircon crystal grains in sediments—characteristics, classifications, definitions. Geologica Saxonica 59:65–73

Gleißner P, Drüppel K, Becker H (2012) Osmium isotopes and highly siderophile element fractionation in the massif-type anorthosites of the Mesoproterozoic Kunene Intrusive Complex, NW Namibia. Chem Geol 302–303:33–47

Goscombe B, Gray DR (2008) Structure and strain variation at mid-crustal levels in a transpressional orogen: a review of Kaoko Belt structure and the character of West Gondwana amalgamation and dispersal. Gondwana Res 13:45–85

Goscombe B, Gray D, Armstrong R, Foster DA, Vogl J (2005) Event geochronology of the Pan-African Kaoko Belt, Namibia. Precambrian Res 140:103–131

Goudie AS (2005) The drainage of Africa since the Cretaceous. Geomorphology 67:437–456

Goudie AS, Warren A, Jones DKC, Cooke RU (1987) The character and possible origins of the aeolian sediments of the Wahiba Sand Sea, Oman. Geogr J 153(2):231–256

Gray DR, Foster DA, Goscombe B, Passchier CW, Trouw RAJ (2006) ^{40}Ar/^{39}Ar thermochronology of the Pan-African Damaran Orogen, Namibia, with implications for tectonothermal and geodynamic evolution. Precambrian Res 150:49–72

Haddon IG (2005) The sub-Kalahari geology and tectonic evolution of the Kalahari Basin, southern Africa. PhD Thesis, University of the Witwatersrand

Haddon IG, McCarthy TS (2005) The Mesozoic–Cenozoic interior sag basins of Central Africa: the Late-Cretaceous–Cenozoic Kalahari and Okavango basins. J Afr Earth Sci 43:316–333

Haggerty SE, Raber E, Naeser CW (1983) Fission track dating of kimberlitic zircons. Earth Planet Sc Lett 63:41–50

Halverson GP, Hoffman PF, Schrag DP, Maloof AC, Rice AHN (2005) Toward a Neoproterozoic composite carbon-isotope record. Geol Soc Am Bull 117:1181–1207

Hanson RE (2003) Proterozoic geochronology and tectonic evolution of southern Africa. In: Yoshida M, Windley BF, Dasgupta S (eds) Proterozoic East Gondwana: supercontinent assembly and breakup. J Geol Soc Lond 206:427–463

Hanson RE, Wardlaw MS, Wilson TJ, Mwale G (1993) U–Pb zircon ages from the Hook granite massif and Mwembeshi dislocation: constraints on Pan-African deformation, plutonism, and transcurrent shearing in central Zambia. Precambrian Res 63:189–209

Hoal KO, Hoal BG, Griffin WL, Armstrong RA (2000) Characterization of the age and nature of the lithosphere in the Tsumkwe region, Namibia. Commun Geol Surv Namib 12:21–28

Hoffman PF, Hawkins DP, Isachsen CE, Bowring SA (1996) Precise U–Pb zircon ages for early Damaran magmatism in the Summas mountains and Welwitschia inlier, northern Damara belt, Namibia. Commun Geol Surv Namib 11:47–52

Huntsman-Mapila P, Kampunzu AB, Vink B, Ringrose S (2005) Cryptic indicators of provenance from the geochemistry of the Okavango Delta sediments, Botswana. Sediment Geol 174:123–148

Jackson MPA, Hudec MR, Hegarty KA (2005) The great West African tertiary coastal uplift: fact or fiction? A perspective from the Angolan divergent margin. Tectonics 24:TC6014. doi:10.1029/2005TC001836

Johnson SP, Rivers T (2004) A review of the Mesoproterozoic to early Palaeozoic magmatic and tectonothermal history of central southern Africa: implications for Rodinia and Gondwana reconstructions. Geoscience Africa 2004, Abstr.-Vol., Univ. Witwatersrand, Johannesburg, South Africa, pp 309–310

Jung S, Hoffer E, Hoernes S (2007) Neo-proterozoic rift-related syenites (Northern Damara Belt, Namibia): geochemical and Nd–Sr–Pb–O isotope constraints for mantle sources and petrogenesis. Lithos 96:415–435

Kampunzu AB, Armstrong R, Modisi MP, Mapeo RBM (1999) The Kibaran Belt in Southwest Africa: ion microprobe U–Pb zircon data and definition of the Kibaran Ngami Belt in Botswana, Namibia and Angola. Gondwana Res 2(4):571–572

Kampunzu AB, Armstrong RA, Modisi MP, Mapeo RBM (2000) Ion microprobe U–Pb ages on detrital zircon grains from the Ghanzi group: implications for the identification of a Kibaran-age crust in northwest Botswana. J Afr Earth Sci 30:579–587

Key RM, Armstrong RA (2000) Geology and geochronology of pre-Katangan igneous and meta-igneous rocks north of the Lufilian Arc in northwest Zambia. Abstr.-Vol, pp 36–37

Key RM, Liyungu AK, Njamu FM, Somwe V, Banda J, Mosley PN, Armstrong RA (2001) The western arm of the Lufilian Arc in NW Zambia and its potential for copper mineralization. J Afr Earth Sci 33:503–528

Kisters AFM, Jordaan LS, Neumaier K (2004) Thrust-related dome structures in the Karibib district and the origin of orthogonal fabric domains in the south Central Zone of the Pan-African Damara belt, Namibia. Precambrian Res 133: 283–303

Kokonyangi J, Armstrong R, Kampunzu AB, Yoshida M, Okudaira T (2004) U–Pb zircon geochronology and petrology of granitoids from Mitwaba (Katanga, Congo): implications for the evolution of the Mesoproterozoic Kibaran belt. Precambrian Res 132:79–106 (Geocongress 2000: 27th earth science congress of the GSSA)

Kokonyangi JW, Kampunzu AB, Armstrong R, Yoshida M, Okudaira T, Arima M, Ngulube DA (2006) The Mesoproterozoic Kibaride belt (Katanga, SE DR Congo). J Afr Earth Sci 46:1–35

Kröner A, Rojas-Agramonte Y, Hegner E, Hoffmann K-H, Wingate MTD (2010) SHRIMP zircon dating and Nd isotopic systematics of Palaeoproterozoic migmatic orthogneisses in the Epupa Metamorphic complex of northeastern Namibia. Precambrian Res 183:50–69

Krueger S, Leuschner DC, Ehrmann W, Schmiedl G, Mackensen A, Diekmann B (2008) Ocean circulation patterns and dust supply into the South Atlantic during the last glacial cycle revealed by statistical analysis of kaolinite/chlorite ratios. Mar Geol 253:82–91

Lancaster PJ, Storey CD, Hawkesworth CJ, Dhuime B (2011) Understanding the roles of crustal growth and preservation in the detrital zircon record. Earth Planet Sc Lett 305:405–412

Lawrence RL, Cox R, Mapes RW, Coleman DS (2011) Hydrodynamic fractionation of zircon age populations. Geol Soc Am Bull 123:295–305

Liégeois J-P, Abdelsalam MG, Ennih N, Ouabadi A (2013) Metacraton: Nature, genesis and behavior. Gondwana Res 23:220-237

Lobo-Guerrero Sanz A (2005) Pre- and post-Katangan Granitoids of the Greater Lufilian Arc—geology, geochemistry, geochronology and metallogenetic significance. PhD Thesis, University of the Witwatersrand

Luft JL, Chemale F, Armstrong R (2011) Evidence of 1.7- to 1.8-Ga Collisional Arc in the Kaoko Belt, NW Namibia. Int J Earth Sci (Geol Rundsch) 100:305–321

Maslin MA, Pancost RD, Wilson KE, Lewis J, Trauth MH (2012) Three and half million year history of moisture availability of South West Africa: evidence from ODP site 1085 biomarker records. Palaeogeogr Palaeoclimatol Palaeoecol 317–318:41–47

Master S, Rainaud C, Armstrong RA, Phillips D, Robb LJ (2005) Provenance ages of the Neoproterozoic Katanga Supergroup (Central African Copperbelt), with implications for basin evolution. Int J Afr Earth Sci 42:41–60

Mayer A, Hofmann AW, Sinigoi S, Morais E (2004) Mesoproterozoic Sm–Nd and U–Pb ages for the Kunene Anorthosite Complex of SW Angola. Precambrian Res 133:187–206

McCourt S, Armstrong RA, Kampunzu AB, Mapeo RBM, Morais E (2004) New U–Pb SHRIMP ages on zircons from the Lubango region, southwest Angola: insights into the Proterozoic evolution of south-western Africa. Geoscience Africa 2004, Abstr.-Vol., Univ. Witwatersrand, Johannesburg, South Africa, pp 438–439

McGee B, Halverson GP, Collins AS (2012) Cryogenian rift-related magmatism and sedimentation: south-western Congo Craton, Namibia. J Afr Earth Sci 76:34–49

Meert JG (2012) What's in a name? The Columbia (Paleopangaea/Nuna) supercontinent. Gondwana Res 21:987–993

Milési J-P, Boutin P, Deschamps Y (2004) Géologie et principales minéralisations d'Afrique centrale [Geology and major ore deposits of Central Africa], 1:4.000.000, 1 sheet. Bureau de recherches géologiques et minières. Orléans

Milési J-P, Toteu SF, Deschamps Y, Feybesse JL, Lerouge C, Cocherie A, Penaye J, Tchameni R, Moloto-A-Kenguemba G, Kampunzu HAB, Nicol N, Duguey E, Leistel JM, Saint-Martin M, Ralay F, Heinry C, Bouchot V, Doumnang Mbaigane JC, Kanda Kula V, Chene F, Monthel J, Boutin P, Cailteux J (2006) An overview of the geology and major ore deposits of Central Africa: explanatory note for the 1:4,000,000 map "Geology and major ore deposits of Central Africa". J Afr Earth Sci 44:571–595

Miller RMcG (1997) The Ovambo Basin of Northern Namibia. In: Shelly (ed) Sedimentary basins of the world, vol 3. African Basins, pp 237–268

Miller RMcG, Schalk KEL (1980) Geological map of South West Africa/Namibia; scale 1:1.000.000, 4 sheets. Geological survey of the Republic of South Africa and South West Africa/Namibia, Windhoek

Moore A, Blenkinsop T (2002) The role of mantle plumes in the development of continental-scale drainage patterns: the southern African example revisited. S Afr J Geol 105:353–360

Ngoyi K, Liégeois J-P, Demaiffe D, Dumont P (1991) Age tardi-ubendien (Protérozoïque inférieur) des dômes granitiques de l'arc cuprifère zaïro-zambien. CR Acad Sci Paris 313:83–89

Nikitina LP, Marin YB, Skublov SG, Korolev NM, Saltykova AK, Zinchenko VN, Chissupa HM (2012) U–Pb Age and Geochemistry of Zircon from Mantle Xenoliths of the Katoka and Kat-115 Kimberlitic Pipes (Republic of Angola). Dokl Earth Sci 445:840–844

Oyhantçabal P, Siegesmund S, Wemmer K, Passchier CW (2011) The transpressional connection between Dom Feliciano and Kaoko Belts at 580-550 Ma. Int J Earth Sci (Geol Rundsch) 100:379–390

Pedreira AJ, De Waele B (2008) Contemporaneous evolution of the Palaeoproterozoic–Mesoproterozoic sedimentary basins of the São Francisco–Congo Craton. Geol Soc SP 294:33–48

Pereira E, Tassinari CCG, Rodrigues JF, Van-Dúnem MV (2011) New data on the deposition age of the volcano-sedimentary Chela Group and its Eburnean basement: implications to post-Eburnean crustal evolution of the SW of Angola. Comunicações Geológicas 98:29–40

Pichevin L, Cremer M, Giraudeau J, Bertrand P (2005) A 190 ky record of lithogenic grain-size on Namibian slope: forging a tight link between past wind-strength and coastal upwelling dynamics. Mar Geol 218:81–96

Pirajno F (1994) Mineral resources of anorogenic alkaline complexes in Namibia. Aust J Earth Sci 41:157–168

Porada H, Berhorst V (2000) Towards a new understanding of Neoproterozoic-Early Palæozoic Lufilian and northern Zambezi Belt in Zambia and the Democratic Republic of Congo. J Afr Earth Sci 30(3):727–771

Prendergast MD, Wingate MTD (2012) Zircon geochronology of late Archean komatiitic sills and their felsic country rocks, south-central Zimbabwe: a revised age for the Reliance komatiitic event and its implications. Precambrian Res 229:105–124

Pupin J-P (1980) Zircon and granite petrology. Contirb Miner Petrol 73:207–220

Pupin J-P, Persoz F (1999) Le zircon, marquer de mélanges magmatiques à l'origine de granites de l'association subalcaline ferro-potassique. CR Acad Sci II A 328(1):9–16

Rainaud C, Master S, Armstrong RA, Robb LJ (2003) A cryptic Mesoarchean terrane in the basement to the central African Copperbelt. J Geol Soc Lond 160:11–14

Rainaud C, Master S, Armstrong RA, Robb LJ (2005) Geochronology and nature of the Palaeoproterozoic basement in the Central African Copperbelt (Zambia and the Democratic Republic of Congo), with regional implications. J Afr Earth Sci 42:1–31

Rapela CW, Fanning CM, Casquet C, Pankhurst RJ, Spalletti L, Poiré D, Baldo EG (2011) The Rio de la Plata craton and the adjoining Pan African/brasiliano terranes: their origins and incorporation into south-west Gondwana. Gondwana Res 20:673–690

Reid DL, Cooper AF, Rex DC, Harmer RE (1990) Timing of post-Karoo alkaline volcanism in southern Namibia. Geol Mag 127:427–433

Ringrose S, Huntsman-Mapila P, Downey W, Coetzee S, Fey M, Vanderpost C, Vink B, Kemosidile T, Kolokose D (2008) Diagenesis in Okavango fan and adjacent dune deposits with implications for the record of palaeo-environmental change in Makgadikgadi–Okavango–Zambezi basin, northern Botswana. Geomorphology 101:544–557

Rino S, Komiya T, Windley BF, Katayama I, Motoki A, Hirata T (2004) Major episodic increases of continental crustal growth determined from zircon ages of river sand; implications for mantle overturns in Early Precambrian. Phys Earth Planet 146:369–394

Rino S, Kon Y, Sato W, Maruyama S, Santosh M, Zhao D (2008) The Grenvillian and Pan-African orogens: world's larges orogenies through geologic time, and their implications on the origin of superplume. Gondwana Res 14:51–72

Robles-Cruz SE, Escayola M, Jackson S, Galí S, Pervov V, Watangua M, Gonçalves A, Carles Melgarejo J (2012) U–Pb SHRIMP geochronology of zircon from the Catoca kimberlite, Angola: implications for diamond exploration. Chem Geol 310–311:137–147

Rollinson HR, Whitehouse M (2011) The growth of the Zimbabwe Craton during the late Archaean: an ion microprobe U–Pb zircon study. J Geol Soc Lond 168:941–952

Schärer U, Berndt J, Scherer EE, Kooijman E, Deutsch A, Klostermann J (2012) Major geological cycles substantiated by U–Pb and εHf_i of detrital zircon grains from the Lower Rhine Basin. Chem Geol 294–295:63–74

Schmitt AK, Emmermann R, Trumbull RB, Bühn B, Henjes-Kunst F (2000) Petrogenesis and $^{40}Ar/^{39}Ar$ geochronology of the Brandberg Complex, Namibia: evidence for a major mantle contribution in metaluminous and peralkaline granites. J Petrol 41:1207–1239

Schmitt RS, Trouw RAJ, Passchier CW, Medeiros SR, Armstrong R (2012) 530 Ma syntectonic syenites and granites in NW Namibia—their relation with collision along the junction of Damara and Kaoko belts. Gondwana Res 21:362–377

Seth B, Kröner A, Mezger K, Nemchin AA, Pidgeon RT, Okrusch M (1998) Archaean to Neoproterozoic magmatic events in the Kaoko belt of NW Namibia and their geodynamic significance. Precambrian Res 92:341–363

Seth B, Armstrong RA, Brandt S, Villa IM, Kramers JD (2003) Mesoproterozoic U–Pb and Pb–Pb ages of granulites in NW Namibia: reconstructing a complete orogenic cycle. Precambrian Res 126:147–168

Seth B, Armstrong RA, Büttner A, Villa IM (2005) Time constraints for Mesoproterozoic upper amphibolite facies metamorphism in NW Namibia: a multi-isotopic approach. Earth Planet Sc Lett 230:355–378

Shi N, Schneider R, Beug H-J, Dupont LM (2001) Southeast trade wind variations during the last 135 kyr: evidence from pollen spectra in eastern South Atlantic sediments. Earth Plante Sci Lett 187:311–321

Singletary SJ, Hanson RE, Martin MW, Crowley JL, Bowring SA, Key RM, Ramokate LV, Direng BB (2003) Geochronology of basement rocks in the Kalahari Desert, Botswana, and implications for regional Proterozoic tectonics. Precambrian Res 121:47–71

Slejko FF, Demarchi G, Morais E (2002) Mineral chemistry and Nd isotopic composition of two anorthositic rocks from the Kunene complex (South Western Angola). J Afr Earth Sci 35:77–88

Söderlund U, Hofmann A, Klausen MB, Olsson JR, Ernst RE, Persson P-O (2012) Towards a complete magmatic barcode for the Zimbabwe craton: Baddeleyite U–Pb dating of regional dolerite dyke swarms and sill complexes. Precambrian Res 183:388–398

Tack L, Wingate MTD, De Waele D, Meert J, Belousava E, Griffin B, Tahon A, Fernandez-Alonso M (2010) The 1375 Ma "Kibaran event" in Central Africa: prominent emplacement of bimodal magmatism under extensional regime. Precambrian Res 180:63–84

Thomas DSG, Shaw PA (1990) The deposition and development of the Kalahari Group sediments, Central Southern Africa. J Afr Earth Sci 10(1–2):187–197

Thover E, D'Agrella-Filho MS, Trindade RIF (2006) Paleomagnetic record of Africa and South America for the 1200–500 Ma interval, and evaluation of Rodinia and Gondwana assemblies. Precambrian Res 147:193–222

Torrealday HI, Hitzman M, Stein HJ, Markley RJ, Armstrong R, Broughton D (2000) Re–Os and U–Pb Dating of the vein-hosted mineralizations at the Kansanshi copper deposit, Northern Zambia. Econ Geol 95(5):1165–1170

Torsvik TH (2003) The Rodinia jigsaw puzzle. Science 300:1379–1381

Veevers JJ (2007) Pan-Gondwanaland post-collisional extension marked by 650–500 Ma alkaline rocks and carbonatites and related detrital zircons: a review. Earth Sci Rev 83:1–47

Walraven F, Rumvegeri BT (1993) Implications of whole-rock Pb–Pb and zircon evaporation dates fort he early metamorphic history of the Kasaï craton, Southern Zaïre. J Afr Earth Sci 16:395–404

Wang X, Dong Z, Zhang J, Qu J, Zhao A (2003) Grain size characteristics of dune sands in the central Taklimakan Sand Sea. Sediment Geol 161:1–14

Wang CY, Campbell IH, Allen CM, Williams IS, Eggins SM (2009) Rate of growth of the preserved North American continental crust: evidence from Hf and O isotopes in Mississippi detrital zircons. Geochim Cosmochim Ac 73:712–728

Wang CY, Campbell IH, Stepanov A, Allen CM, Burtsev IN (2011) Growth rate of the preserved continental crust: II. Constraints from Hf and O isotopes in detrital zircons from Greater Russian Rivers. Geochim Cosmochim Acta 75:1308–1345

Wanke H, Wanke A (2007) Lithostratigraphy of the Kalahari Group in northeastern Namibia. J Afr Earth Sci 48:314–328

Wendorff M, Key RM (2009) The relevance of the sedimentary history of the Grand Conglomerat Formation (Central Africa) to the interpretation of the climate during a major Cryogenian glacial event. Precambrian Res 172:127–142

Wigand M, Schmitt AK, Trumbull RB, Villa IM, Emmermann R (2004) Short-lived magmatic activity in anorogenic subvolcanic complex: 40Ar/39Ar and ion microprobe U–Pb zircon dating of the Erongo, Damaraland Province, Namibia. J Volcanol Geoth Res 130:285–305

Yang J, Gao S, Chen C, Tang Y, Yuan H, Gong H, Xie S, Wang J (2009) Episodic crustal growth of North China as revealed by U–Pb age and Hf isotopes of detrital zircons from modern rivers. Geochim Csmochim Acta 73:2660–2673

Yang S, Zhang F, Wang Z (2012) Grain size distribution and age population of detrital zircons from the Changjiang (Yangtze) River system, China. Chem Geol 296–297:26–38