# Paleogeography and Tectono-Stratigraphy of Carboniferous-Permian and Triassic 'Karoo-Like' Sequences of the Congo Basin

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## 7.1 Introduction

The Congo Basin (CB) of central Africa, also known as the 'Cuvette centrale', was first systematically explored geologically during the 1950s when this region was part of a Belgian colony. This early exploration included extensive field mapping, regional magnetic and seismic surveys (e.g. Jones et al. 1959; Evrard 1960), and drilling of two boreholes (Samba-1 and Dekese-1), each ca. 2 km deep (Cahen et al. 1959, 1960). This work defined the structural setting and stratigraphy of the CB, culminating in the completion of the Geological Map of Zaire (Lepersonne 1974), now the Democratic Republic of Congo (DRC). All research materials from this exploration period are archived in the Royal Museum for Central Africa (RMCA), in Tervuren, Belgium.

Subsequently, during the 1970s, renewed petroleum exploration led to the acquisition of additional geophysical data and the drilling by 'Esso-Zaire' of two deeper wells (Gilson-1 and Mbandaka-1), each ca. 4.5 km in depth (Esso-Zaire 1981a, b). This data has largely remained proprietary, and only short summaries of this work were published (Lawrence and Makazu 1988; Daly et al. 1991, 1992). Since then, very little new geologic or geophysical data has been acquired across the CB (e.g. Kadima et al. 2011; Sachse et al. 2012; Linol 2013). For that reason, the stratigraphy of this unusually large (ca. 1.8 million km$^2$) sedimentary basin remains very poorly characterized, preventing a more modern basin analysis. Today, there is still controversy about the basic definition of its major depositional sequences (i.e. supersequences) and the age of their bounding unconformities.

Here, new field observations are integrated with re-examination of the old literature (in French) and the available seismic- and well-data to resolve some of these major stratigraphic uncertainties, focusing on the 'Karoo-like' (Carboniferous-Permian and Triassic) sequences of the CB. In addition, U-Pb dating of detrital zircons from core samples of two of the deep boreholes characterizes the source provenances for these sediments and helps to constrain the paleogeography of central Africa during the late Paleozoic and early Mesozoic.

## 7.2 Geological Setting

The CB is surrounded by Precambrian basement and peripheral Pan African fold-and-thrust belts of Neoproterozoic carbonate and siliclastic platform sequences (Fig. 7.1; see

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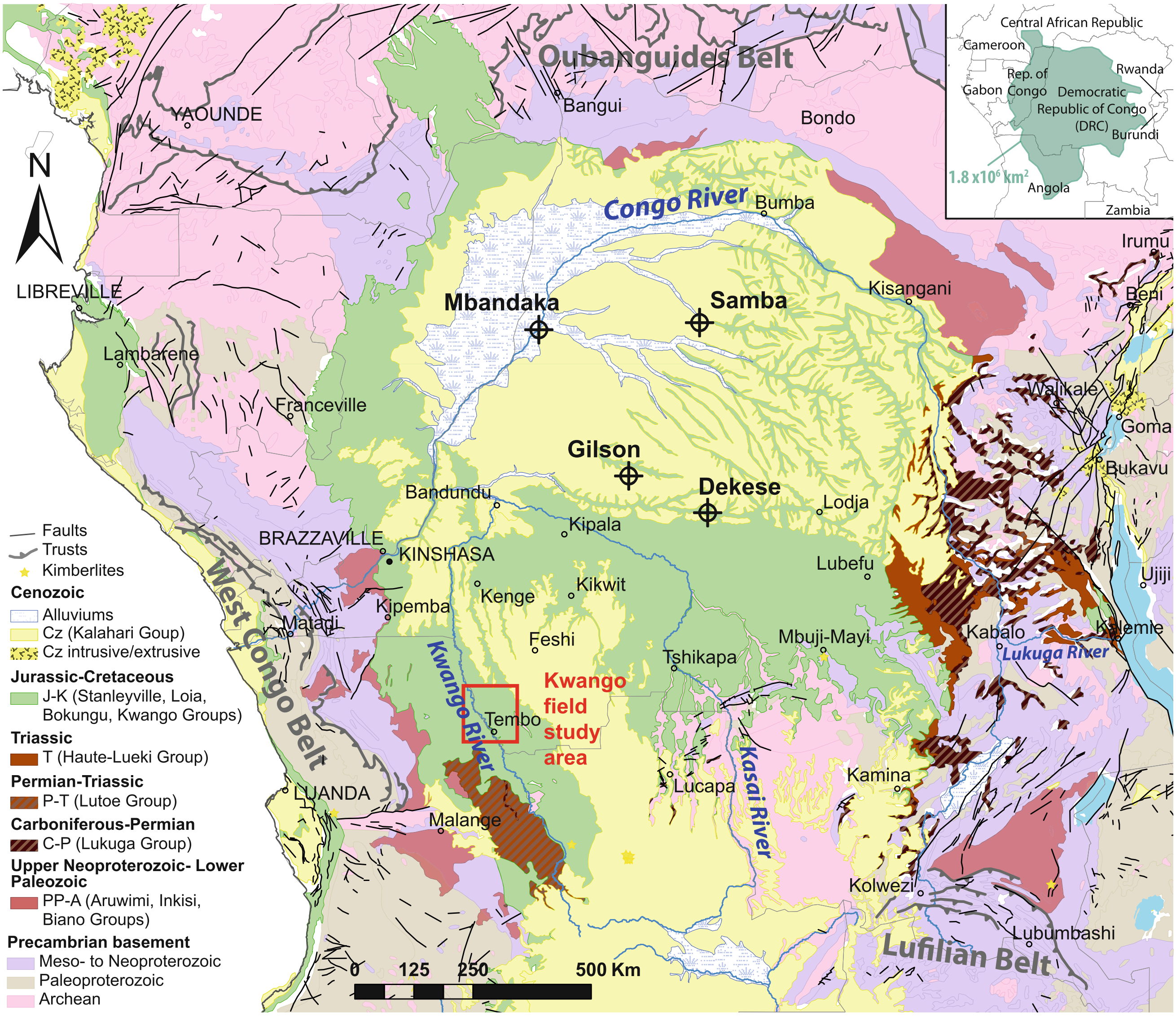


**Fig. 7.1** Simplified geological map of the CB with location of the studied four deep boreholes and the field area in the Kwango Valley (*red box*). Precambrian geology is from de Wit et al. (1988), and Phanerozoic sedimentary cover compiled from various national geological maps (e.g. Lepersonne 1974; de Carvalho 1981; Desthieux 1995; Rolin 1995)

Chaps. 2 and 3, this Book). Along the margins of the basin these Pan African mobile belts are overlapped by widespread upper Neoproterozoic to lower Paleozoic 'red-beds' (e.g. Lepersonne 1978; Poidevin 1985), and Carboniferous to Triassic sequences that contain a rich Gondwanan flora, similar to those from southern Africa, Madagascar and India (Bose and Kar 1978; Cahen and Lepersonne 1978). In the CB, these successions are peneplained and in turn covered by Jurassic-Cretaceous and Cenozoic sediments (see Chaps. 8, 9 and 10, this Book).

The lowermost, upper Neoproterozoic to lower Paleozoic succession of red-beds comprises the Inkisi, Aruwimi and Biano (formerly Upper Kundelungu) Groups, each about 1,000–1,500 m thick (Lepersonne 1974; see also Chap. 6, this Book), unconformably overlying the West Congo, Oubanguides and Lufilian fold-and-thrust belts (Fig. 7.1). These sequences, mainly of quartzitic and conglomeratic red sandstones and siltstones, were deposited with regional paleocurrents to the south (Alvarez et al. 1995; Master et al. 2005), and all are considered to post-date the Pan African orogens (ca. 530–650 Ma; de Wit et al. 2008). Their stratigraphy, however, is poorly constrained by field observations and to date there are no reliable age constraints (Tait et al. 2011).

The overlying Carboniferous to Triassic sequences in the CB correspond to the Lukuga and Haute Lueki Groups that outcrop mostly in eastern DRC (Figs. 7.1 and 7.2). Along the southwestern margin of the basin, in northern Angola, their stratigraphic equivalents correspond to the Lutoe and Cassange Groups (de Carvalho 1981). These sequences

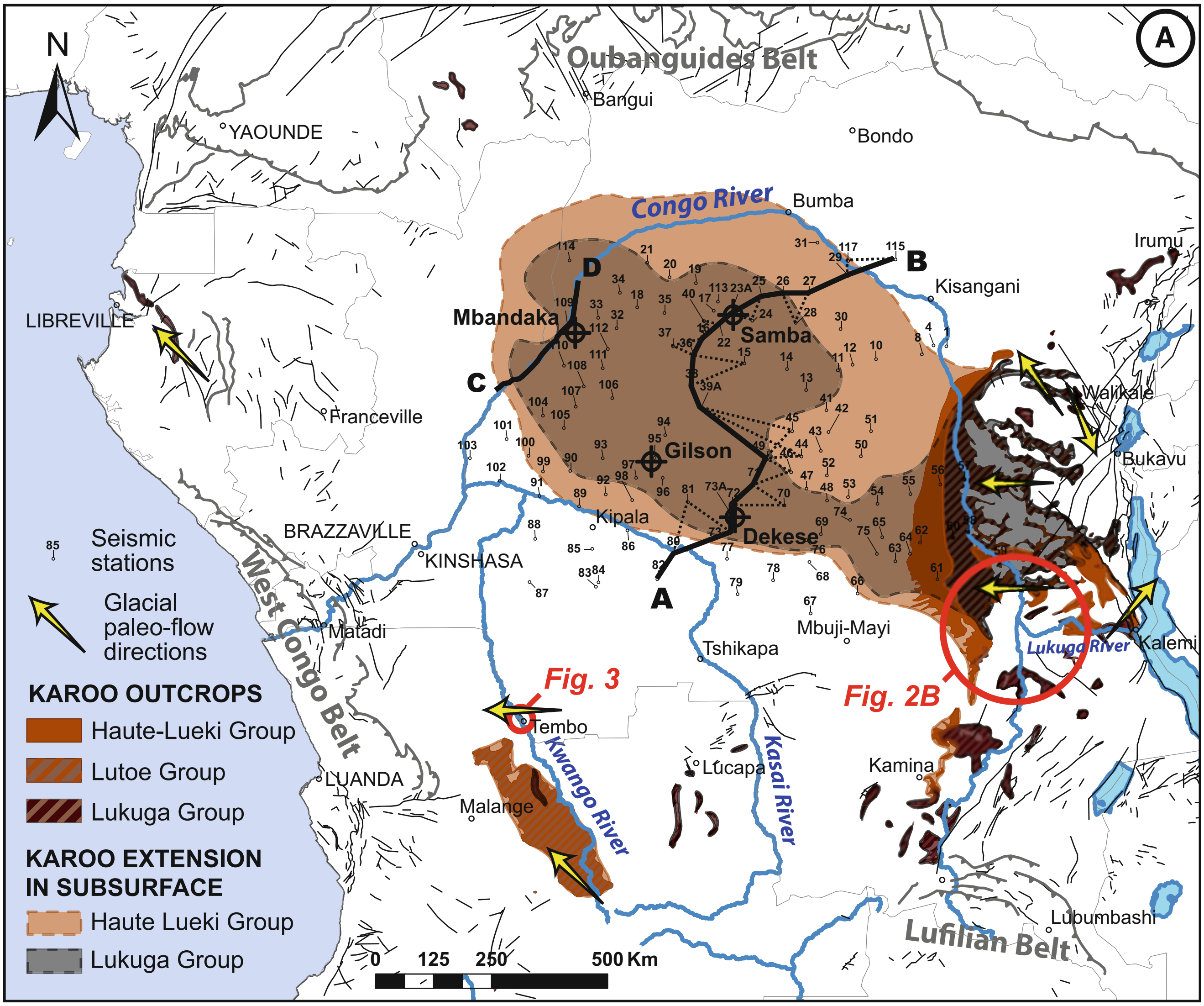


**Fig. 7.2** (continued)

comprise glacial and periglacial, fossiliferous deposits with black shales that pass upward into arid continental sediments (Cahen and Lepersonne 1978; Cahen 1981), tracking the characteristic climatic evolution of central Gondwana during the late Paleozoic and early Mesozoic (e.g. Veevers et al. 1994; Milani and de Wit 2008). Similar Gondwana sequences, in east Africa (in Kenya and Tanzania; e.g. Kreuser 1984; Wopfner and Diekmann 1996), Madagascar (e.g. Rakotosolofo et al. 1999) and southern Africa (Johnson et al. 1996, 2006) are generally referred to as the Karoo Supergroup.

### 7.2.1 The Lukuga Group

The Lukuga Group is between about 300 m and 600 m thick along the eastern margin of the CB, best preserved within large west-facing paleo-glacial valleys (Fig. 7.2). Other glacial relics, also deposited with predominant paleocurrents oriented to the west, are found sporadically along the southern margin of the basin, in the Kasai and Kwango regions of southern DRC and northern Angola (Asselberghs 1947; Lepersonne 1951; Rocha-Campos 1976), and along the western and northern margins of the CB, in Gabon (the Agoula Series; e.g. Mounguengui et al. 2002) and Central African Republic (CAR) (the Mambere Formation; e.g. Rolin 1995).

The type-section of the Lukuga Group in eastern DRC is divided into two subgroups (Fig. 7.2B):

1. The Lower Subgroup comprises two formations of tillites: 'the lower and upper, mainly glacial beds' (Cahen and Lepersonne 1978), separated by black shales. It overlies a major unconformity on Precambrian

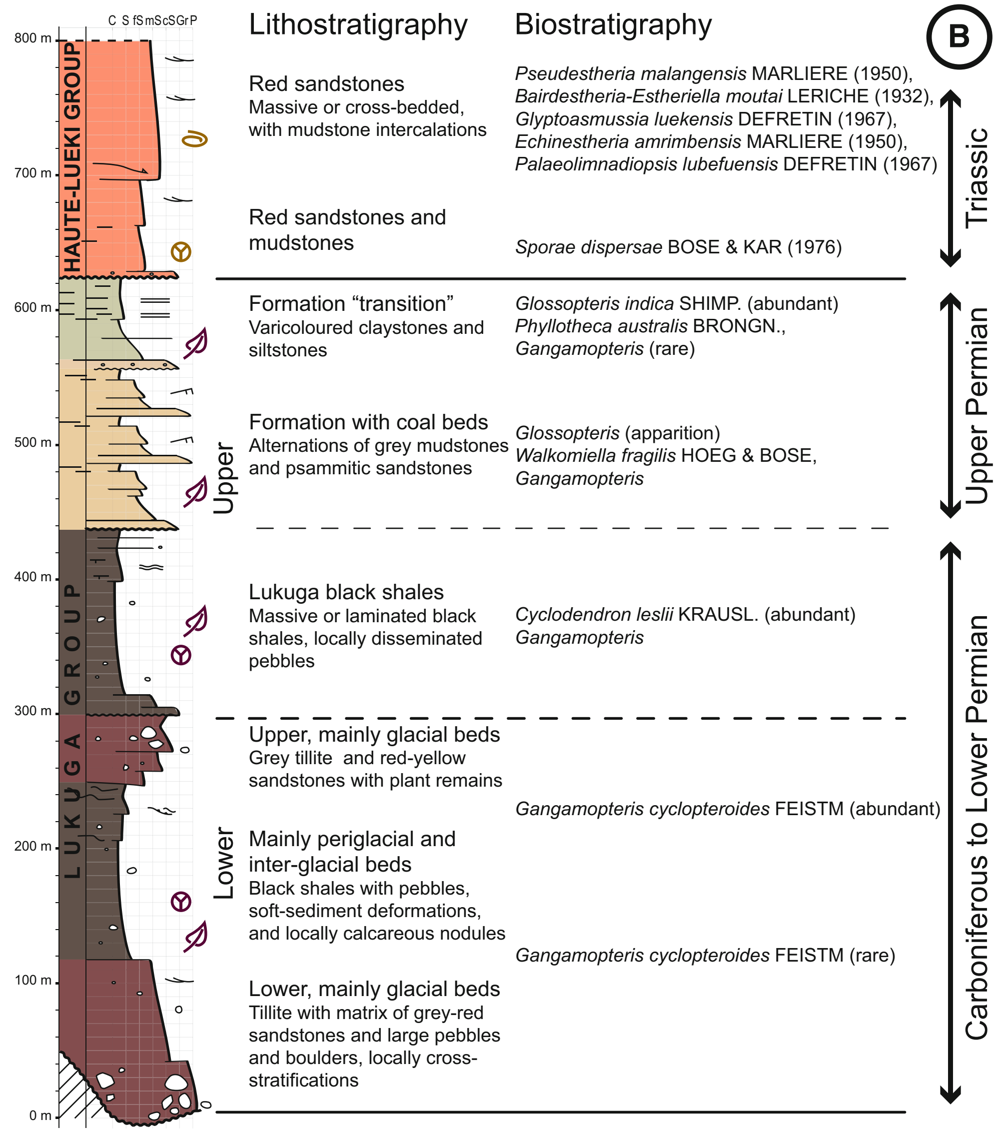


**Fig. 7.2** (**A**) Map of Carboniferous-Permian and Triassic sequences of the CB, showing their vast extent in subsurface (as inferred from borehole and seismic data), and (**B**) stratigraphic type-section along the eastern margin of the basin (reconstructed from descriptions summarized in Cahen and Lepersonne (1978) and Cahen (1981)); see Figs. 7.4 and 7.10 for lithologic and biostratigraphic symbols. Seismic profiles A–B and C–D (*thick black lines*) are re-interpreted in Fig. 7.6 and 7.8, respectively

basement in the east (e.g. the Kibaran Belt), and is estimated to be between 100 m to 300 m thick in total, mainly based on the field studies of Fourmarier (1914), Jamotte (1932) and Boutakoff (1948).

2. The Upper Subgroup is known in more detail because of coal exploration and mining (Cahen and Lepersonne 1978). It includes 120 m thick black shales (‘the Lukuga Black Shale’), overlain by a 20 m to 125 m thick formation of sandstones and mudstones with thin coal beds, and then a ‘Transitional Formation’ of varicolored mudstones, between 30 m and 65 m thick. The top of this sequence is an erosion surface, covered by a conglomerate bed at the base of the Haute Lueki Group.

The Lukuga Group is dated by paleobotany from the Carboniferous to the Upper Permian (Bose and Kar 1978). This compares well with other records of the late Paleozoic glaciation of Gondwana, such as the Dwyka and Ecca Groups of southern Africa (Johnson et al. 2006; Isbell et al. 2008). The lowermost glacial sediments are difficult to date accurately, however, in southern South Africa uppermost beds (the Waaipoort Formation) underlying the Dwyka Group contain plant remains no older than Middle Tournaisian (350 Ma) and have dropstones and soft sediment deformation structures of glacial origin (Streel and Theron 1999; Opdyke et al. 2001). Thus, the onset of the glaciation in southern (and central) Africa is likely to be

Early Carboniferous (e.g. Milani and de Wit 2008; Montañez and Poulsen 2013). The termination of the glaciation is constrained by palynostratigraphy to the Early Permian (e.g. Visser 1995; Modie and Le Hérissé 2009), and with geochronology on zircons from tuff horizons within the lowermost Ecca Group (the Prince Albert Formation), dated at 288 Ma (Bangert et al. 1999).

### 7.2.2 The Haute Lueki Group

The overlying Haute Lueki Group is between 50 m and 200–500 m thick in southeastern DRC, best preserved in NNW-trending Cenozoic rift valleys (e.g. Luama), west of Lake Tanganyika (Fig. 7.2). Outcrops are relatively poorly described (Cahen 1954; Lombard 1961) and generally divided into two:

1. A lower subgroup of grey-brown fine sandstones and siltstones with red mudstones, up to 150 m in thickness.
2. An upper subgroup of cross-bedded red sandstones, between 150 m and 300 m thick.

The Haute Lueki Group is dated locally in its lower part by palynology as Lower Triassic (Bose and Kar 1976). Ostracods and phyllopods collected from this group are common in the Cassange Group of Angola (Cahen 1981), which also yields Triassic fish fossils (e.g. Antunes et al. 1990). Thus, all these sequences of the CB are time-equivalent to the Beaufort Group of southern Africa (Catuneanu et al. 2005; Johnson et al. 2006).

## 7.3 New Stratigraphic Basin Analysis

Below, new field observations are described from the Kwango region of the southwest CB, and the old seismic- and well-data in the center of the basin are re-examined to facilitate regional correlations of the 'Karoo-like' (Carboniferous-Permian and Triassic) sequences. This is then complemented with U-Pb dates of detrital zircons from core samples of two of the deep boreholes (Samba-1 and Dekese-1) to constrain the ages and the source provenances of these sediments.

### 7.3.1 Field Observations

Fieldwork was conducted (in 2008) along the Kwango River of the southwest DRC to document the structure and stratigraphy of exposed rocks and sediments in this remote region (Figs. 7.1 and 7.2A for location; Linol 2013). Here, Archean bedrock (the Dibaya Complex; Cahen et al. 1984) outcrops locally within waterfalls and rapids near Tembo, forming a major nick-point 150 m high (Fig. 7.3). This bedrock comprises mainly grey granites and migmatites (dated to >2.6 Ga; Cahen et al. 1984), strikes E-W, and dips 30–40° to the north to disappear in the CB beneath red sandstones of the Kwango Group (see Chap. 8, this Book).

Within the bottom half of the Kwango nick-point, a lowermost succession of well-bedded purplish-red conglomerates and siltstones was mapped along a 5 km long section, onlapping to the south and to the north across the crystalline bedrock (Fig. 7.3). This succession, maximum 30 m in thickness, comprises superimposed thick bars (1–3 m) of massive and cross-bedded conglomerates that grade upward into red siltstones with intercalations of micro-conglomerates (e.g. Fig. 7.3A). Pebble imbrications and cross-stratifications indicate river bed-load deposition with a general paleocurrent to the west (e.g. Fig. 7.3B). These conglomerates also contain boulder-size dropstones (e.g. Fig. 7.3C) that suggest a proximal glacial environment (Eyles and Eyles 1992). Thus, this lowermost fluvial-glacial succession can be correlated confidently to the other glaciogenic deposits of the Lukuga Group (Asselberghs 1947), and attests to the vast extent of ice-sheets across a paleo-relief located in east and south-central Africa during the Carboniferous (Dwyka) glaciation of Gondwana.

Field observations in the Kwango Valley show that this succession is tilted 5–15° to the south and to the west, and is unconformably overlain by tabular formations of white and red sandstones of the Jurassic-Cretaceous Kwango Group (Chap. 8, this book for details). This is consistent with the other descriptions of the Lukuga Group along the eastern margin of the CB (e.g. Jamotte 1932), but further field studies are needed to precisely characterize this angular unconformity regionally.

### 7.3.2 Seismic- and Well-Data

The two different seismic and drilling methods completed in the 1950s and in the 1970s represent the only subsurface dataset available to study the structure of the central CB.

#### 7.3.2.1 Borehole Locations and Depths

The four deep boreholes drilled in the center of the CB (Figs. 7.1 and 7.2A for locations) were examined using the original core and cutting descriptions, the well logs (Cahen et al. 1959, 1960; Esso-Zaire 1981a, b), and by re-logging the cores that are stored at the RMCA museum in Belgium (Linol 2013). Figure 7.4 presents the four new reconstructed litho-stratigraphic sections: Samba, Dekese, Gilson and Mbandaka, together with overlapping seismic refraction data.

The Samba-1 borehole (0°09′45″N; 21°15′10″E) is located along the Maringa River, in the northeastern part of the central CB. It cuts through 1,167 m thick subhorizontal, red to green, bedded sandstones and mudstones (Units S1 to S5; Fig. 7.4), and then 871 m thick red quartzitic sandstones

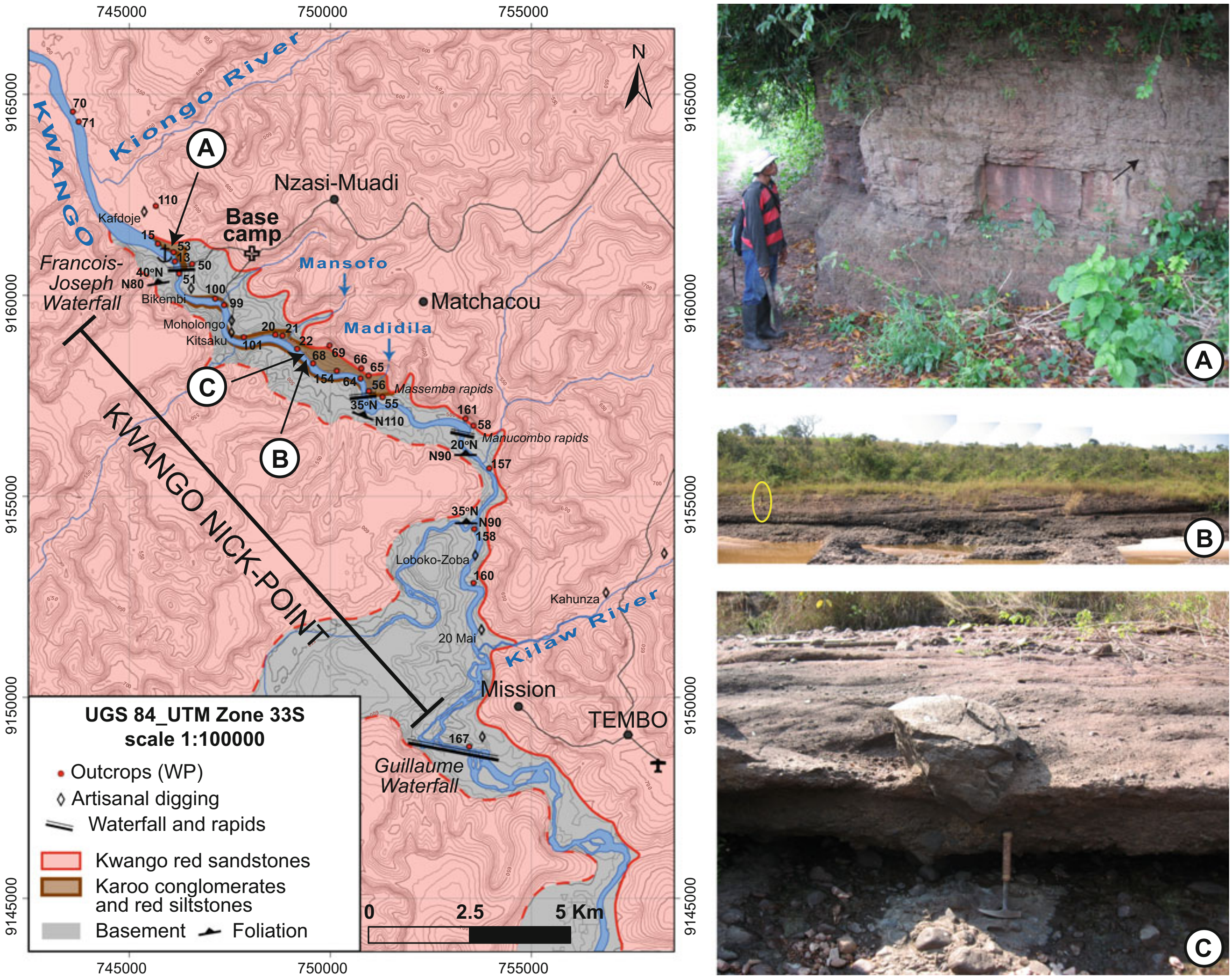


**Fig. 7.3** Field map with location of outcrops and photos of fluvial-glacial conglomerates and red siltstones in the area surrounding the Kwango nick-point, between Tembo and Nzasi-Muadi, in southwestern DRC. (**A**) Red siltstones including lenses of micro-conglomerates (*arrow*) at the Port of Nzasi-Muadi (WP13). (**B**) Large-scale cross-bedded conglomerates with paleocurrents to the west (WP22); note person for scale (*yellow ellipse*). (**C**) Example of large boulder dropstone (WP22); hammer for scale

(Unit S6). The hole ends at a depth of −2,038 m, and does not reach the base of the quartzites.

The Dekese-1 borehole (3°27′26″S; 21°24′28″E) is located about 400 km to the south of Samba, in the south-central part of the basin. It cuts through 755 m thick subhorizontal, predominantly red sandstones (Units D1 to D6), and then 962 m thick soft-deformed (slumped) black shales and diamictites (Units D7 to D9). This section also rests on a basement of red quartzitic sandstones (Unit D10). The hole ends at a depth of −1,956 m, and does not reach the base of the quartzites (Fig. 7.4).

The Mbandaka-1 borehole (0°02′30″S; 18°14′10″E) is located along the Congo River, in the northwestern part of the central CB. It cuts through 844 m thick red to green bedded sandstones and mudstones (Units M1 to M4), and then 3,147 m thick red-brown quartzitic sandstones (Units M5 and M6), red-orange conglomerates (Unit M7) and grey-brown quartzitic and conglomeratic sandstones interbedded with siltstones (Units M8 and M9; Fig. 7.4). This section overlies carbonated siltstones and dolomites (Unit M10), and the hole stops at a depth of −4,343 m in a relative soft basement, which was interpreted to be halite (Esso-Zaire 1981a), as the deepest core recovered (at the depth of −4,147 m) shows large nodules of anhydrite (Fig. 7.5).

The Gilson-1 borehole (02°44′10″S; 19°54′30″E) is located about 350 km to the southeast of Mbandaka, in the south-central part of the basin. It cuts through 998 m thick interbedded red sandstones with mudstones (Units G1 to G5), and then 2,269 m thick red sandstones (Unit G6), dark brown siltstones (Unit G7) and red-brown mudstones and conglomeratic sandstones (Units G8 to G10). This section overlies 1,229 m thick interbedded sandstones with limestones (Unit G11) and dolomites (Unit G12). The hole

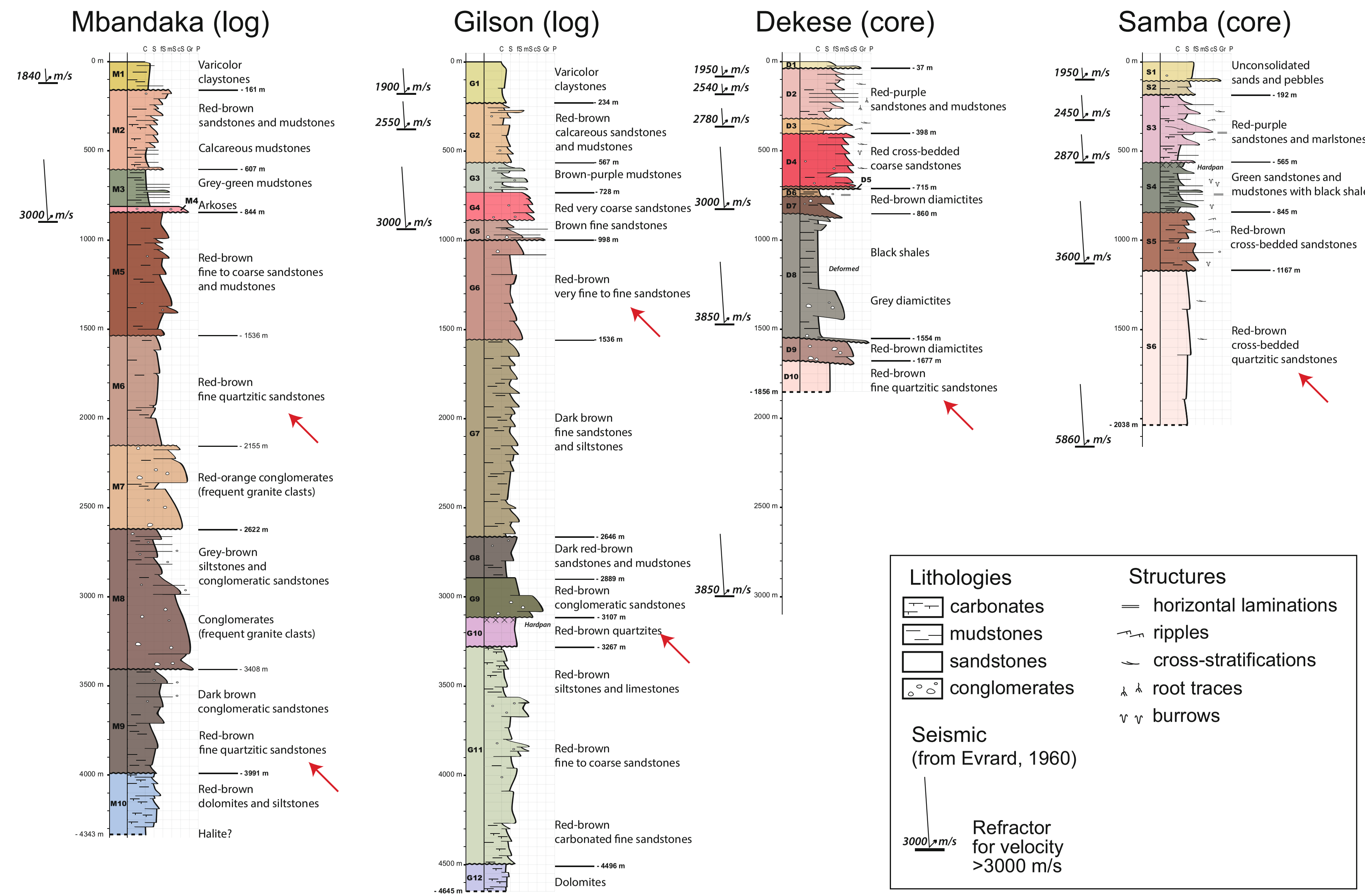


**Fig. 7.4** Revised stratigraphic sections from the four deep boreholes drilled in the center of the CB in the 1950s and 1970s (Figs. 7.1 and 7.2A for locations). Note that the main geological contacts are also identified in seismic refraction analyses (Fig. 7.6). *Red arrows* show the different formations of red quartzites

**Fig. 7.5** Photo of drill core (No. 8) from the depth interval −4,139 m to −4,147 m in the Mbandaka-1 borehole. The cut face of the core shows thinly laminated (stromatolithic?) dolomitic fine sands and dark shales with large nodules of anhydrite. The core is 90 mm in diameter

terminates at a depth of −4,645 m in the dolomites (Fig. 7.4).

#### 7.3.2.2 Seismic Refraction Data from the 1950s

The old (1952–1956) seismic refraction surveys essentially determined the sediment thicknesses at different locations (e.g. 111 stations) across the entire central CB (Fig. 7.2A). The depths of the different seismic discontinuities (reflectors) were calculated at each seismic station, and because the sedimentary packages were considered largely tabular and the horizontal velocities much higher than the vertical velocities, the calculated depths were corrected using an arbitrary reduction of 10 % on the observed velocities (Evrard 1960). Comparison of results with the well-data shows that all the main geological contacts were systematically determined (Fig. 7.4).

An 850 km long, N–S reference profile across the Samba and Dekese sections is shown in Fig. 7.6. Along this refraction profile five distinct seismic units are identified:

1. Basement rocks with very high velocities (>5,200 m/s) rapidly rise along the southern part of the profile, from a depth of −3,000 m at Dekese (station 72) to a depth of −400 m (station 82) over a distance of 250 km (Fig. 7.6). Along the southern margin of the CB, this bedrock corresponds to the Kasai and NE Angola Cratons (Cahen et al. 1984), and here named the Kasai and Kwango Highs (Fig. 7.7).
2. A marked seismic contrast with a high velocity range (4,200–4,600 m/s) defines a tectonic high in the center of the profile (between stations 39A and 49), and progressively rises northward to the surface (station 115) where it links with outcropping upper Neoproterozoic quartzitic sandstones of the Aruwimi Group (Lepersonne 1974). In the four deep boreholes in the center of the basin, this seismic discontinuity also corresponds to the tops of quartzitic sandstones, which have distinct high velocities (>4,200 m/s). Although these lithologies (e.g. quartzites) occur at different stratigraphic levels (see Fig. 7.4).
3. A distinct seismic unit with intermediate velocities (3,600 to 3,900 m/s) occurs in a limited zone, 170 km wide, of the southern part of the profile (Fig. 7.6). In the Dekese section (station 72), this unit corresponds to 694 m thick black shales with diamictites (Unit D8), dated by palynostratigraphy to the Permian and attributed to the Lukuga Group (Cahen et al. 1960; Boulouard and Calandra 1963).
4. An overlying unit of lower velocities (2,400 to 3,600 m/s) stretches continuously across the profile, between 300 m (station 73) to maximum 1,000 m thick at Samba (station 23A). In the four deep boreholes, it is dated biostratigraphically to the Upper Jurassic and middle Cretaceous (Cahen et al. 1959, 1960; Grekoff 1960; Defretin-Lefranc 1967; Maheshwari et al. 1977; Colin 1981; Colin and Jan du Chêne 1981). This main seismic unit displays major lateral variation along the profile (Fig. 7.6). In the south the seismic velocities are relatively low (~3,000 m/s), and in the Dekese section (station 72) these correspond to predominantly cross-bedded red coarse sandstones (Units D2 to D5). By contrast, in the north their lateral equivalents have higher velocities (~3,600 m/s), which in the Samba section (station 23A) correspond to alternating green mudstones and black shales with lesser sandstones (Units S3 to S5). This discernible change in seismic velocity reflects a major N-S lateral change in the late Mesozoic lithostratigraphy (see also Chap. 8, this Book).
5. A thin uppermost seismic unit of low velocity range (1,800–2,200 m/s), with a maximum thickness of 200 m

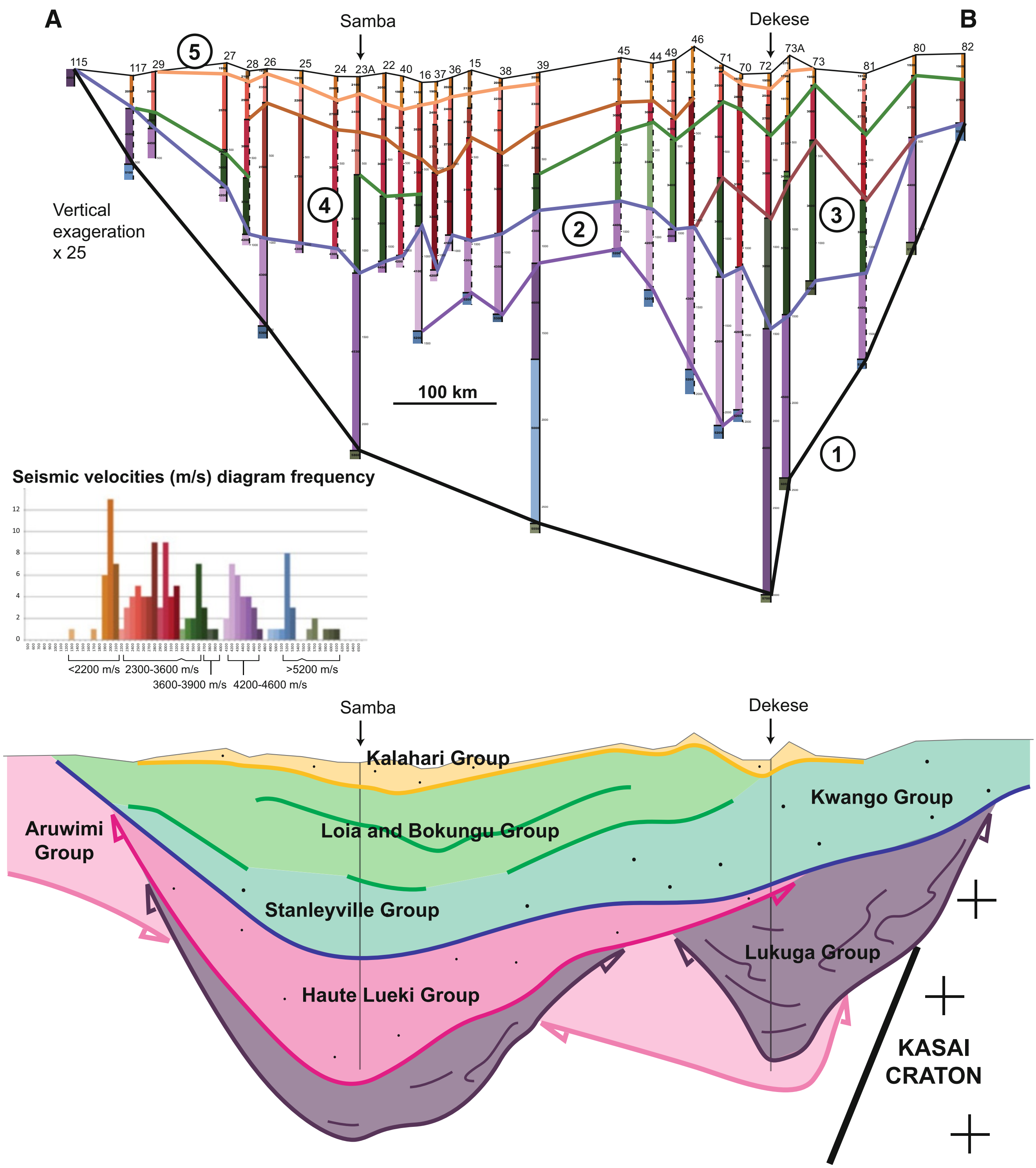


**Fig. 7.6** N–S seismic refraction profile (data are from Evrard 1960), 850 km long across the Samba and Dekese sections (Fig. 7.2A for location). The *upper* profile shows five distinct units separated by seismic discontinuities: (1) basement rocks (>5,200 m/s); (2) quartzitic sandstones (4,200–4,600 m/s); (3) black shales and diamictites (3,600–3,900 m/s); (4) poorly consolidated sandstones and mudstones (3,000 and 3,300–3,600 m/s); and (5) uppermost unconsolidated material (<2,200 m/s). *Lower figure* is a schematic interpretation (*arrows* pointing up represent cross-cutting relationships)

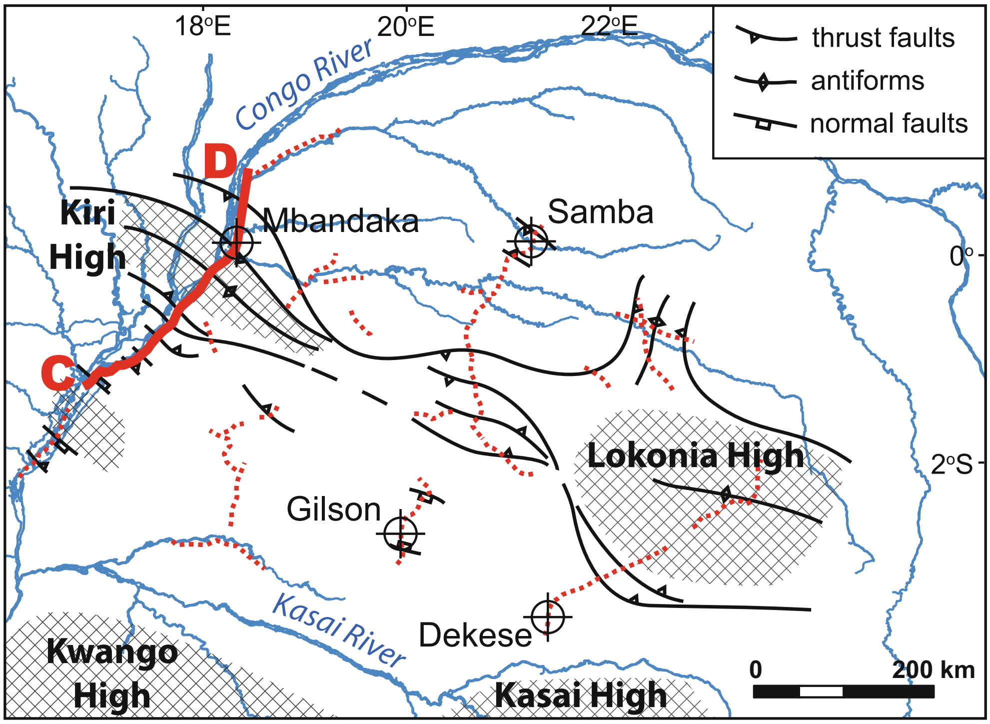


**Fig. 7.7** Structural sketch map of the central CB with location of seismic reflection lines and the four deep boreholes (modified from Daly et al. 1992). The profile C–D (*thick red line*) is re-interpreted in Fig. 7.8. The structures may represent a large-scale NW–SE 'flower structure', or an extensional tilt (see text for further explanation)

at station 22, occurs both in the south and in the northern parts of the profile (Fig. 7.6). In the boreholes (Fig. 7.4), this unit corresponds to unconsolidated sandstones and claystones (<2,200 m/s), designated to the (Cenozoic) Kalahari Group (Cahen et al. 1959, and 1960; Colin 1981; Colin and Jan du Chêne 1981; Chap. 10, this Book).

#### 7.3.2.3 Seismic Reflection Data from the 1970s

Between 1974 and 1976, petroleum exploration work acquired 36 reflection lines along rivers and roads, discontinuously between the Congo and the Kasai Rivers in the center of the basin (Fig. 7.7 for locations). The first interpretation of these data described a series of two NW-trending basement highs, named the Kiri and Lokonia Highs (Lawrence and Makazu 1988; Daly et al. 1991, 1992). Along the seismic profiles (e.g. Fig. 7.8), truncations of folded sedimentary packages along the flanks of these highs clearly indicate compressive deformation. Accordingly, the highs were interpreted to represent east- and west-verging fold-and-thrust structures ('flower structure' or 'pop-up'; Daly et al. 1991). More recent studies (Crosby et al. 2010; Kadima et al. 2011) have proposed that these reflection data may also be interpreted as a series of rifts and horsts bounded by normal faults, and further suggested the probable influence of salt tectonic associated with deep lying Neoproterozoic evaporites. Thus, whilst the principal structural framework of the CB has been presented as a reticulate fault pattern with transfer faults accommodating offsets between the Kiri and Lokonia Highs, the available seismic data are of poor quality and would require modern reprocessing.

A NE-SW reflection profile, 170 km long along the Congo River and across the Mbandaka section is re-interpreted in Fig. 7.8. This profile shows three major seismic unconformity-bounded sequences, or supersequences, which overlie a 'presumed basement of complex structure' (Daly et al. 1992) capped locally by distinct reflectors of very high amplitude. In the Mbandaka section, these reflectors correspond to massive dolomites grading upward into interbedded brown sandstones with limestones (Unit M10) that can be correlated to Pan African deformed carbonate platforms surrounding the CB, such as for example the upper Neoproterozoic West Congolian Group along the western margin of the basin (Tack et al. 2001; Frimmel et al. 2006; Chap. 3, this book). Along the seismic profile (Fig. 7.8), the carbonates are truncated by a regional erosion surface (interpreted by Daly et al. 1992 as an early Pan African unconformity). This first angular unconformity (U1; Figs. 7.8 and 7.9), located at a depth of −3,991 m in the Mbandaka-1 borehole, is considered to represent the base of the Phanerozoic CB, above which the following three supersequences are recognized:

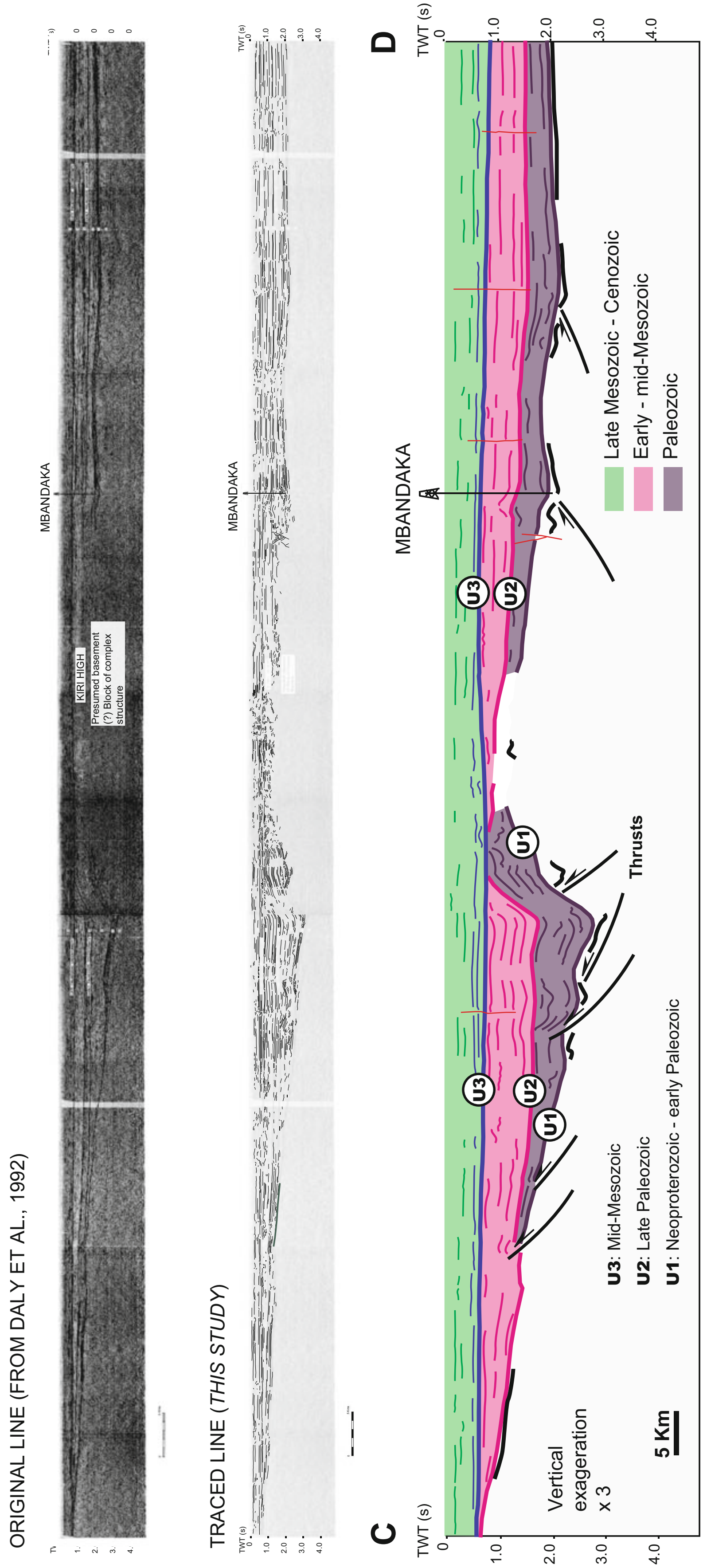


**Fig. 7.8** Re-interpreted NE–SW seismic reflection profile (data are from Daly et al. 1992), 170 km long along the Congo River and across the Mbandaka section (Figs. 7.2A and 7.7 for location). This profile shows three seismic supersequences bounded by regional unconformities (U1, U2, and U3). The time-depth relationship at borehole Mbandaka is shown in Fig. 7.9

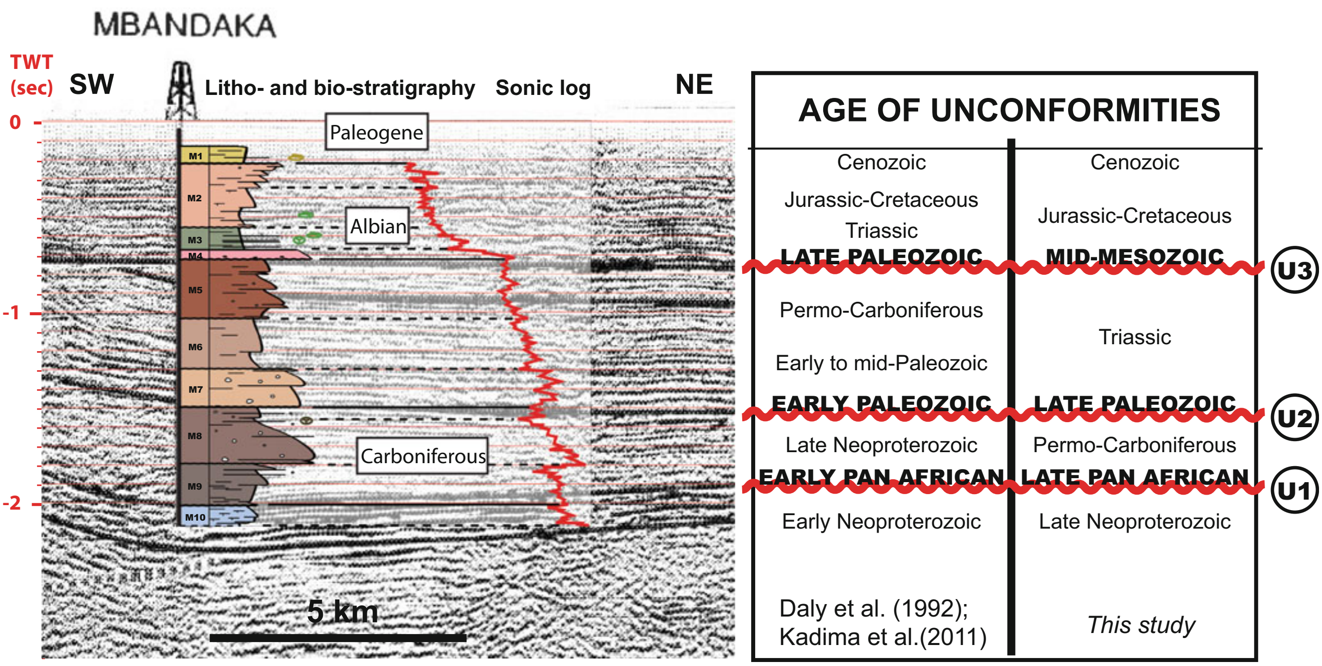


**Fig. 7.9** Re-calibration of the seismic reflection against the Mbandaka well logs (modified from Kadima et al. 2011), and ages of major unconformities. Biostratigraphic data is from the original study of Colin and Jan du Chêne (1981)

1. A lowermost, thick and weakly banded supersequence corresponds in the Mbandaka section to 583 m thick red-brown siltstones coarsening upward into conglomeratic sandstones (Unit M9) and to 786 m thick conglomerates fining upward into grey-brown conglomeratic sandstones with dark siltstone intercalations (Unit M8). Along the seismic profile these two lithostratigraphic units are conformable (Fig. 7.8), and in unison they are truncated by a second regional erosion surface (U2; interpreted as an early Paleozoic unconformity by Daly et al. 1992). A palynological study of the Mbandaka section (Colin and Jan du Chêne 1981) indicates an age younger than mid-Carboniferous within the underlying grey-brown siltstones (Unit M8), on a core-sample between −2,805 m and −2,825 m depth. This suggests a late Paleozoic age for this second angular unconformity (U2; Figs. 7.8 and 7.9).
2. A thick middle succession represented by a discontinuously banded supersequence corresponds in the Mbandaka section to 467 m thick red-orange conglomerates (Unit M7), 619 m thick red-brown fine quartzitic sandstones (Unit M6) and 692 m thick red-brown coarse sandstones with siltstone intercalations (Unit M5). Along the seismic profile (Fig. 7.8), these units are truncated by a very conspicuous, third regional erosion surface (U3) that was interpreted as a late Paleozoic unconformity by Daly et al. (1992). However, this unconformity is at a depth of −844 m in the Mbandaka section, and directly covered by 40 m thick red arkoses (Unit M4) and fossiliferous grey-green mudstones (Unit M3) dated by biostratigraphy to the Albian-Cenomanian (Colin and Jan du Chêne 1981). This rather suggests a late Mesozoic age for the underlying unconformity (U3; Figs. 7.8 and 7.9).
3. A third and uppermost supersequence corresponds in the Mbandaka section to 683 m thick red arkoses and green mudstones coarsening upward into carbonated sandstones (Units M2 to M4), and to 161 m thick varicoloured claystones (Unit M1), dated to the middle Cretaceous and Paleogene, respectively (Colin and Jan du Chêne 1981).

In summary, the seismic reflection data from the 1970s reveals a Phanerozoic development of the CB punctuated by two regional episodes of deformation that previously were interpreted by Daly et al. (1992) to be related to: (1) the Pan African collisions during the end Precambrian and early Cambrian (~530–650 Ma), and (2) a possible phase of distant contraction induced by development of the Cape Fold Belt in southern Africa during the Permian-Triassic (~250 Ma). A recalibration of the seismic reflection against the Mbandaka well logs (i.e. Integrated Travel Time of the Sonic Log), tied to the litho- and bio-stratigraphy (Fig. 7.9), shows that the two lower, Carboniferous-Permian and Triassic supersequences (Units M5 to M9) unconformably overlie deformed Pan African carbonate-siliclastic rocks (Unit M10). These two supersequences are separated by a regional late Paleozoic unconformity (U2) that possibly relates to far-field deformations resulting of multiple collisional processes flanking the margins of Gondwana (Daly et al. 1992; Trouw and de Wit 1999; Newton et al. 2006; Dabo et al. 2008; see Chap. 11, this book). The uppermost unconformity (U3) is overlain by Jurassic-Cretaceous and Cenozoic sediments

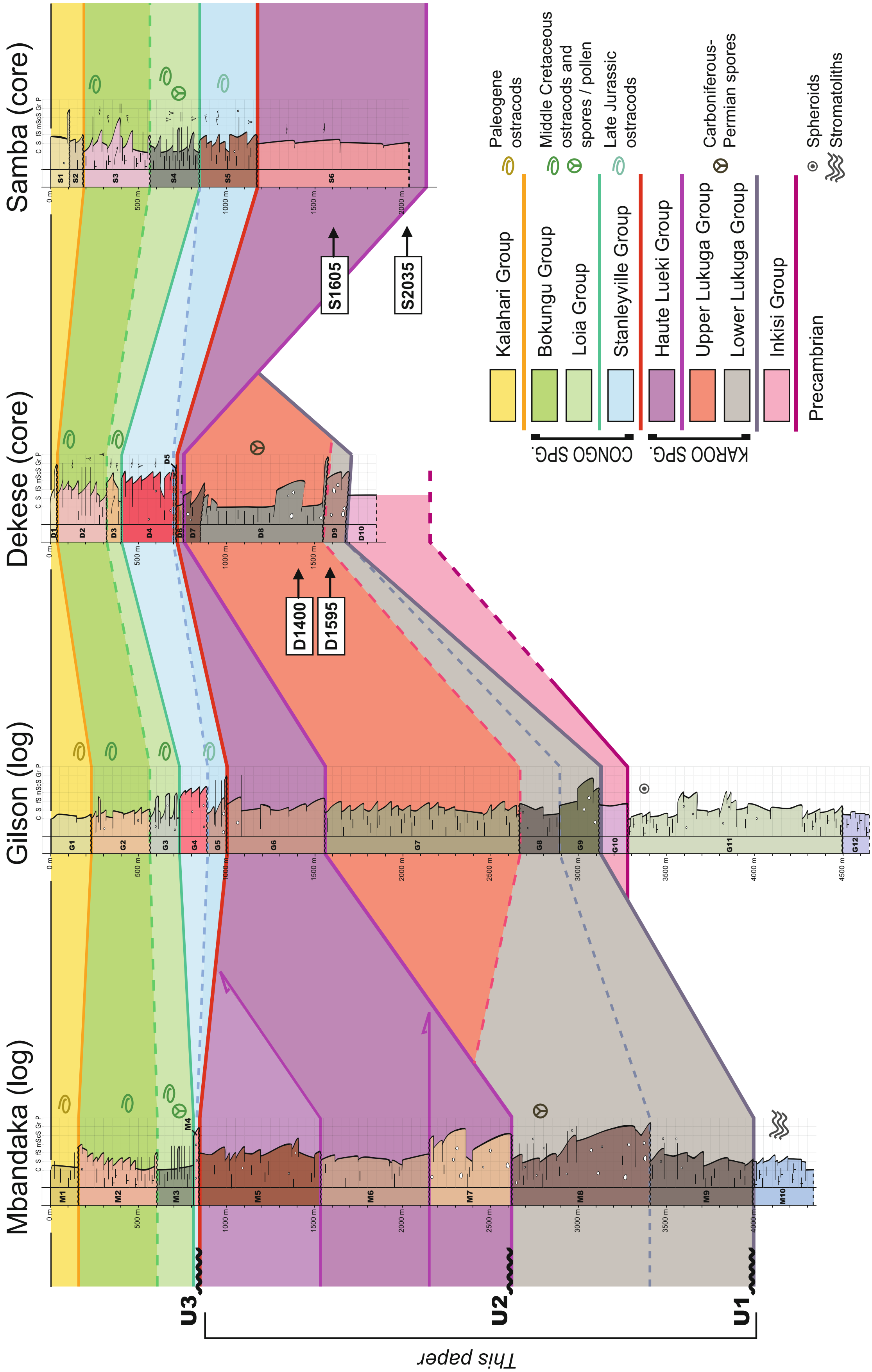


**Fig. 7.10** Litho- and bio-stratigraphic correlations of the Gilson, Mbandaka, Samba and Dekese sections, with location of core-samples with dated detrital zircons

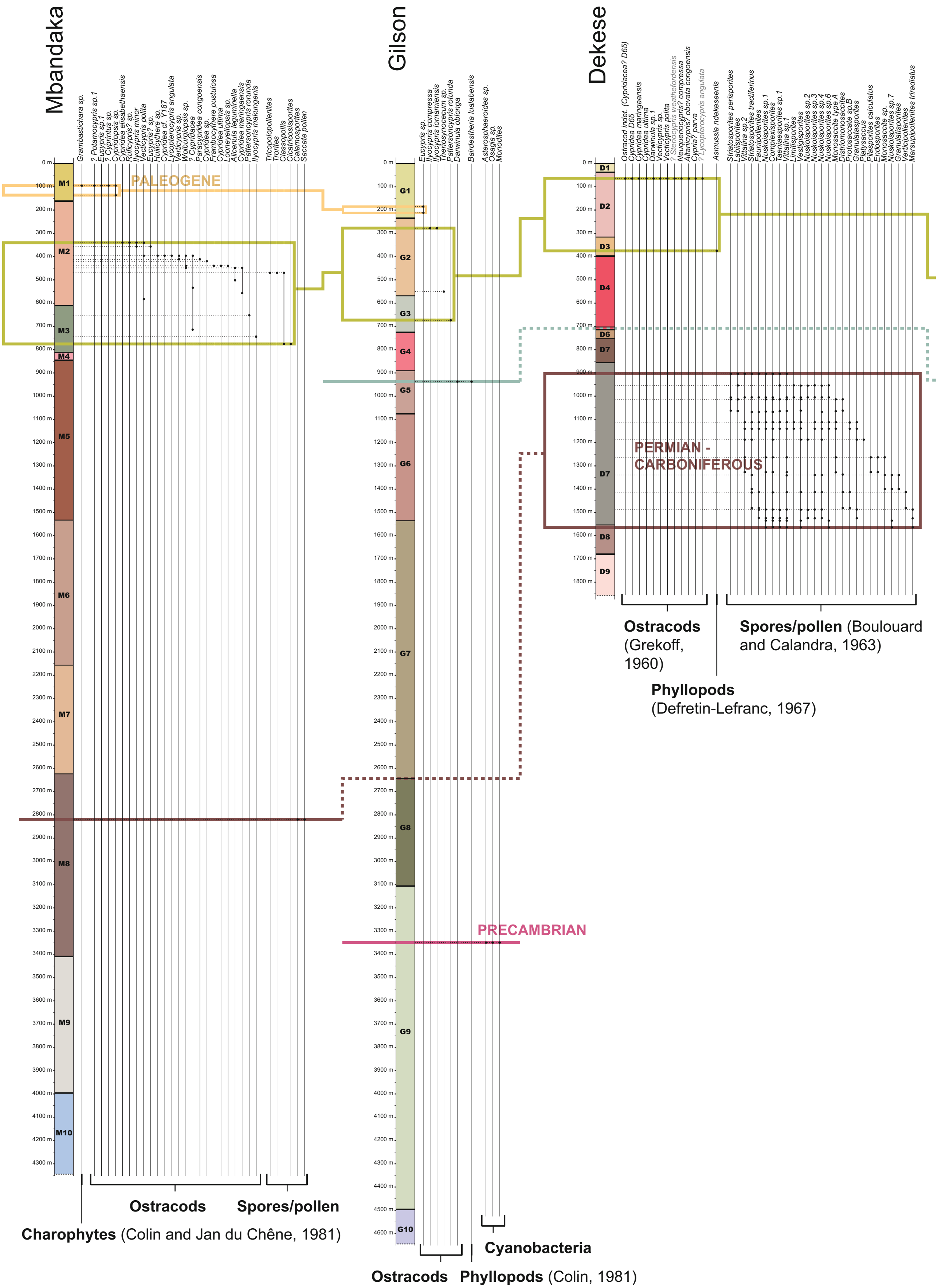


**Fig. 7.11** (continued)

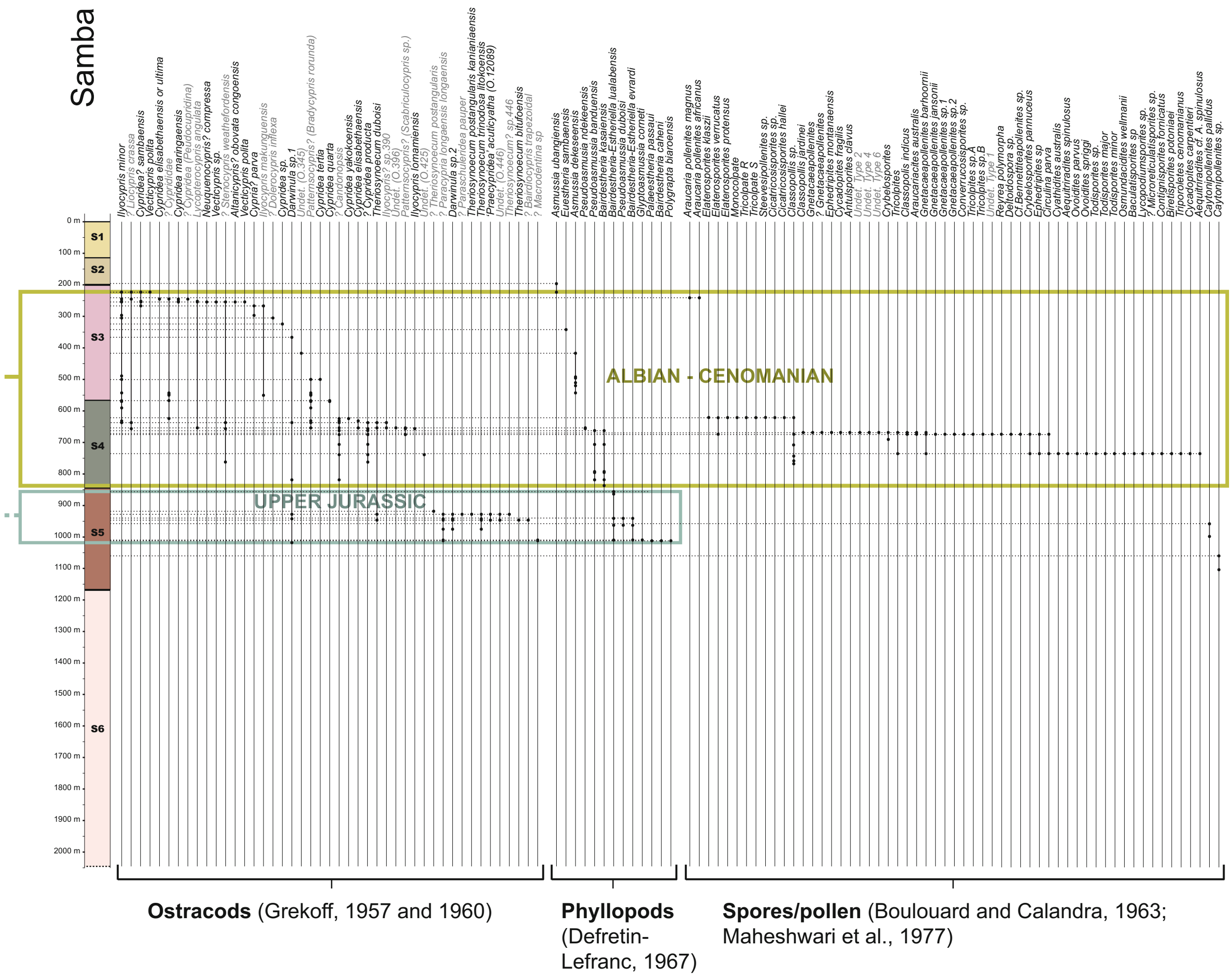


**Fig. 7.11** Revised biostratigraphic data of the Gilson, Mbandaka, Samba and Dekese sections

(Units M1 to M4), and is ascribed to the late Mesozoic (Fig. 7.9). It is here postulated to be related to intracontinental deformation associated with the initial period of break-up of Gondwana, ca. 160–180 Ma (see also Chap. 13, this Book).

## 7.3.3 Seismic-, Litho- and Bio-Stratigraphic Correlations

Based on seismic-, litho- and bio-stratigraphic analyses, new correlations of the Carboniferous-Permian and Triassic ('Karoo-like') sequences are proposed between the type-sections of the Lukuga and Haute-Lueki Groups along the eastern margin of the CB (Fig. 7.2B), and the four deep boreholes in the center of the basin (Fig. 7.10). The available biostratigraphic data of the four borehole-sections is revised in Fig. 7.11.

### 7.3.3.1 Carboniferous-Permian Sequences of the Lukuga Group

In the lower part of the Dekese section (Fig. 7.10), unusually thick and slumped diamictites and black shales (Units D7 to D9), totaling 962 m in thickness, were correlated to the Lukuga Group by Cahen et al. (1960). In this section, palynology within the Unit D8 (Fig. 7.11), between depths of −905 m and −1,565 m, suggests an age ranging from Lower to Upper Permian with the predominance of species: *Nuskoïsporites*, *Vertigisporites* and *Vittatina* (Boulouard and Calandra 1963). These results from the 1960s would need to be re-examined in the light of more recent palynostratigraphic works from south-central and northern Africa (e.g. Modie and Le Hérissé 2009; Gonzalez et al. 2011). Nevertheless, the thick sequence of black shales (Unit D8) in the CB can be correlated confidentially with the distinctive (organic-rich) Permian black shales of the Prince Albert and Whitehill Formations of the Lower Ecca Group in the main Karoo Basin of southern Africa (Johnson et al. 2006).

New correlations of the Lukuga Group in the CB are also proposed with the relatively thick sequences of red-brown conglomeratic sandstones and dark brown siltstones that directly overlie the Pan African carbonate rocks in both, the Gilson (Units G7 to G9, in total 1,571 m thick; Fig. 7.10) and the Mbandaka sections (Units M8 and M9, in total 1,369 m thick). This is only supported by palynostratigraphy, however, in the Mbandaka section between depths of −2,805 m and −2,825 m (Fig. 7.11).

#### 7.3.3.2 Triassic Sequences of the Haute Lueki Group

In the center of the CB, new lithostratigraphic correlations of the Triassic Haute Lueki Group are proposed with the red quartzitic sandstones and mudstones overlying the Carboniferous-Permian black shales and dark brown siltstones in the Dekese (Unit D6, 40 m thick; Fig. 7.10), the Gilson (Unit G6, 538 m thick) and the Mbandaka sections (Units M5 to M7, in total 1,778 m thick). No fossil, or spores and pollen were found in any of these units (Fig. 7.11). However, in the boreholes and seismic data, the top of this quartzitic succession marks a very distinct regional unconformity (U3; Figs. 7.8 and 7.9). This enables correlation of the Haute Lueki Group with the Unit S6 of the Samba section (Fig. 7.10), previously attributed to the upper Neoproterozoic Aruwimi Group by Cahen et al. (1959).

## 7.4 U-Pb Detrital Zircons Geochronology of the Samba and Dekese Cores

U-Pb geochronology of detrital zircons collected from the Samba and Dekese cores (Fig. 7.10 for sample locations) is used to further constrain the stratigraphy and characterize the source provenances of these Carboniferous-Permian and Triassic sequences filling the CB, which in turn help to reconstruct the basin's paleogeography (e.g. Fedo et al. 2003).

255 zircons were analyzed from the Lukuga and Haute Lueki Groups (Tables 7.1 and 7.2; see Linol 2013 and Linol et al. 2014 for details), with two samples from each group (about 50–80 analyses per sample). U-Pb dating was done using AEON's high resolution Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS), coupled to a UP 193 solid-state laser system (New Wave Research) and a desolvation nebulizer system (DSN-100, Nu Instruments). The Nu Plasma MC-ICP-MS is equipped with a special collector block allowing for simultaneous detection of ion signals from masses $^{238}$U to $^{203}$Tl. U and Tl isotopes are measured on Faraday cups, while Pb isotopes are measured on ion counters. For more information about the experimental and analytical procedure see Biggin et al. (2011).

The ages reported in this study are not corrected for common Pb, since correction by the $^{204}$Pb method cannot be applied due to the isobaric interference of $^{204}$Hg, which is a contaminant of the He gas carrying the ablated material from the laser cell to the MC-ICP-MS. All analyses were plotted on Concordia diagrams using Isoplot 3.0 (Ludwig 2003), and most concordant dates (>80 % and <110 % conc.) are compared in frequency age-diagrams (Fig. 7.12).

### 7.4.1 Samples D1400 and D1595 (The Lukuga Group)

Two samples: D1400 and D1595 were taken from diamictites of the Carboniferous-Permian Lukuga Group, at depths of −1,400 m and −1,595 m (Units D8 and D9), respectively, in the lower part of the Dekese section (Fig. 7.10). The zircons from these samples vary in size and shape. The grains are sub-rounded to angular, transparent or smoky grey, and frequently show magmatic zonings (e.g. Fig. 7.13).

74 analyses were performed on 69 grains in sample D1400, and 83 analyses on 79 grains in sample D1595. Results are summarized in Table 7.1.

### 7.4.2 Samples S1605 and S2035 (The Haute Lueki Group)

Two samples: S1605 and S2035 were taken from red quartzitic sandstones of the Triassic Haute Lueki Group at depths of −1,605 m and −2,035 m (Unit S6), respectively, in the lower part of the Samba section (Fig. 7.10). The zircons from this unit are generally small (100–250 μm), elongated, transparent or reddish, and with crystal-shapes that indicate relatively limited transport (e.g. Fig. 7.14). The grains show magmatic zoning and some xenotime overgrows.

64 analyses were performed on 59 grains in sample S1605, and 60 analyses on 48 grains in sample S2035. Results are summarized in Table 7.2.

### 7.4.3 Synthesis and Sources Provenance Analysis

In all samples of the Lukuga and Haute Lueki Groups, four main age-populations were found: 1) early Paleoproterozoic to Archean, 2) mid-Paleoproterozoic (Eburnian), 3) early Neoproterozoic to Mesoproterozoic (Kibaran), and 4) Cambrian to late Neoproterozoic (Pan African), although there

**Table 7.1** Summary of U-Pb detrital zircon dates from samples D1400 and D1595 (the Lukuga Group)

| Age-population | U-Pb Dates ($^{206}Pb/^{207}Pb$) | Notes |
|---|---|---|
| 1. Mesoarchean | One (oldest) zircon dates at 2925 ± 8 Ma | |
| 2. Early Paleoproterozoic to Neoarchean | 10 zircons date between 2.4 Ga and 2.7 Ga, with 9 concentrated between 2566 ± 17 Ma and 2690 ± 16 Ma | Indicate some contributions from Neoarchean aged-terrains. These dates are similar to dated basement rocks in southern DRC and northern Angola (Delhal 1991; Jelsma et al. 2011), western Tanzania and Uganda (Link et al. 2010), and Gabon (Caen-Vachette et al. 1988) |
| 3. Paleoproterozoic (*Second most common age-population*) | 48 zircons date between 1.8 Ga and 2.1 Ga, with 21 restricted between 1852 ± 17 Ma and 1898 ± 17 Ma, and 17 between 2006 ± 17 Ma and 2048 ± 10 Ma | Overlap the conventional Eburnian period (e.g. Cahen et al. 1984). Such dates are common within the Ruwenzori and Ubendian Belts in Uganda and western Tanzania (Lenoir et al. 1995; Nagudi et al. 2003), and within the (Kimezian) basement of the West Congo Belt in western DRC and its large counterpart in eastern Brazil (Tack et al. 2001; Pedrosa-Soares et al. 2008) |
| 4. Mesoproterozoic | 8 zircons date between 1.2 Ga and 1.6 Ga, with 5 bracketed between 1371 ± 18 Ma and 1421 ± 16 Ma | Coincide with the main peak of magmatism of the Kibaran Belt in eastern DRC, Rwanda and Burundi (Kokonyangi et al. 2004; Tack et al. 2010) |
| 5. Early Neoproterozoic to late Mesoproterozoic (*Most common age-population*) | 49 zircons date between 902 ± 27 Ma and 1181 ± 29 Ma | Indicate large contributions from late Mesoproterozoic aged-terrains. These dates are common with the Oubanguides, in particular the central Sahara Belt in CAR and Chad (de Wit et al. 2014, in press), and the Mozambique Belt (Jamal et al. 1999; Bingen et al. 2009) |
| 6. Late Neoproterozoic | 30 zircons date between 544 ± 21 and 865 ± 25 Ma | Indicate large contributions from Pan African aged-terrains, such as the West Congo, Oubanguides, Mozambique and Lufilian Belts |

**Table 7.2** Summary of U-Pb detrital zircon dates from samples S1605 and S2035 (the Haute Lueki Group)

| Age-population | U-Pb dates ($^{206}Pb/^{207}Pb$) | Notes |
|---|---|---|
| 1. Early Paleoproterozoic | One (oldest) zircon dates at 2470 ± 10 Ma | |
| 2. Paleoproterozoic | 6 zircons date between 1952 ± 11 Ma and 2103 ± 5 Ma | Indicate relatively small contributions from Eburnian aged-terrains. Such dates are common in Uganda and western Tanzania (Lenoir 1995; Link et al. 2010), and in Angola and western DRC (de Carvalho et al. 2000; Tack et al. 2001) |
| 3. Mesoproterozoic | 15 zircons date between 1.2 Ga and 1.5 Ga, with only one concordant date at 1399 ± 65 Ma | Kibaran Belt (ca. 1.4 Ga) was not a major source, possibly largely covered by sediments |
| 4. Early Neoproterozoic to late Mesoproterozoic (*Second most common age-population*) | 36 zircons date between 940 ± 9 Ma and 1143 ± 15 Ma | Indicate large contributions from late Mesoproterozoic aged-terrains, dinstinctively younger than the 1.4 Ga Kibaran type-area. Potential source areas have been reported in CAR and Chad (de Wit et al. 2014 in press), and in Mozambique (Jamal et al. 1999; Bingen et al. 2009) |
| 5. Late Neoproterozoic (*Most common age-population*) | 40 zircons date between 579 ± 14 Ma and 817 ± 15 Ma | Correspond to tectonic episodes of the Pan African orogens, such as within the Oubanguides that include multiple structures active between 850 Ma and 550 Ma (Poidevin 1985; Rolin 1995; Toteu et al. 2006) |

are some differences in their proportions that apparently reflect changes in provenance. Figure 7.15 shows a simplified map of basement ages around the CB to evaluate possible source regions for these detrital zircons.

#### 7.4.3.1 Early Paleoproterozoic to Archean (2.4–2.7 Ga and 2.9 Ga)

Early Paleoproterozoic to Archean dates are more common in the samples (D1400 and D1595) from the Lukuga Group (8 grains) in the Dekese section compared to those from the Haute Lueki Group (only 1 grain) in the Samba section (S1605 and S2035). This suggests greater (more proximal) derivations from early Precambrian sources to the glacial sediments in the Dekese section, or that these sources became progressively covered during deposition of the Haute Lueki Group. These 2.4–2.9 Ga sources most likely correspond to the Kasai and Tanzanian Cratons located immediately to the south (~200 km) and to the east (~800 km) of the Dekese section, respectively. This provenance is also supported by the E-W orientations of Carboniferous glacial valleys (Fig. 7.15).

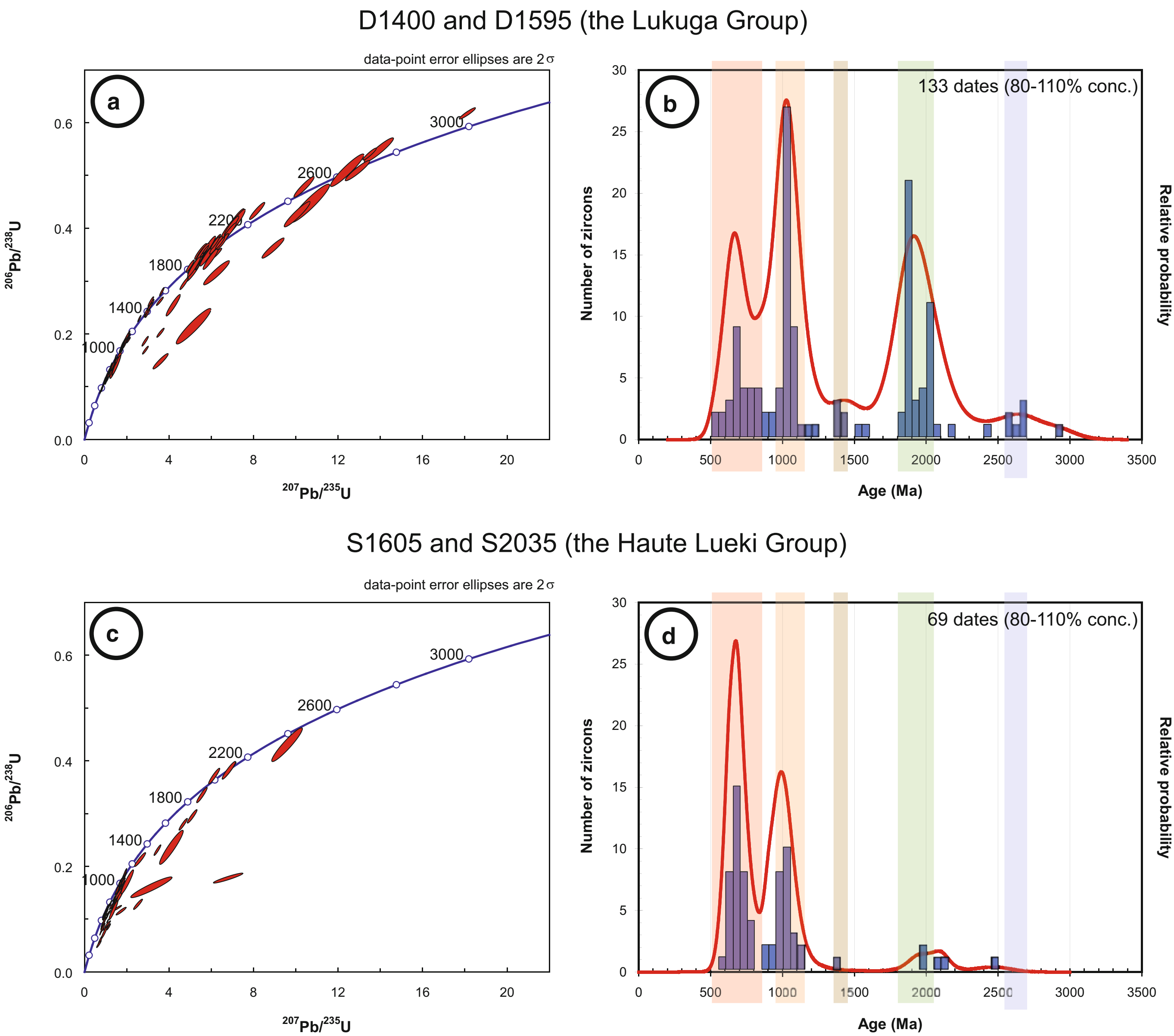


**Fig. 7.12** U-Pb Concordia- and frequency age-diagrams of detrital zircons from core-samples of (**a** and **b**) the Carboniferous-Permian Lukuga Group, and (**c** and **d**) the Triassic Haute Lueki Group, in the lower parts of the Samba and Dekese sections (Fig. 7.10 for sample locations). Main age-populations are *highlighted*

#### 7.4.3.2 Mid-Paleoproterozoic (1.7–2.2 Ga)

Mid-Paleoproterozoic (1.7–2.2 Ga) dates are better represented in the samples from the Dekese section (44 grains) than those from the Samba section (6 grains). This suggests a greater contribution of Eburnian-age rock sequences to the Lukuga Group in the Dekese section, such as found within the Ruwenzori and Ubendian Belts in east Africa (e.g. Lenoir et al. 1995; Link et al. 2010). These Paleoproterozoic dates also overlap with similar age basement rocks along the eastern margin of the CB, in Angola (De Carvalho et al. 2000), western DRC, Gabon and Cameroon (Caen-Vachette et al. 1988; Tack et al. 2001), and large terrains of the same age (Transamazonian) in northeastern Brazil (e.g. Toteu et al. 2001; Lerouge et al. 2006). However, a provenance from westernmost Gondwana (Brazil) is not supported by the westward paleocurrents for the Lukuga Group (Fig. 7.15).

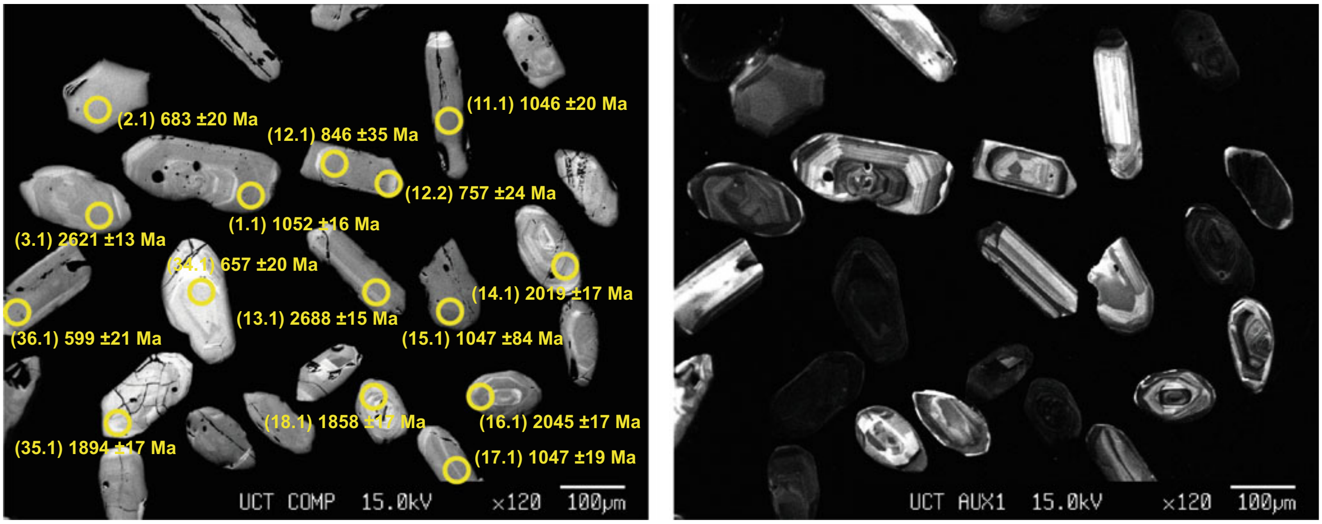


**Fig. 7.13** Example of back-scattered electron (*left* photo) and cathodoluminescence (*right* photo) images of detrital zircons from sample D1595 (the Lukuga Group), with location of laser spots and U-Pb results

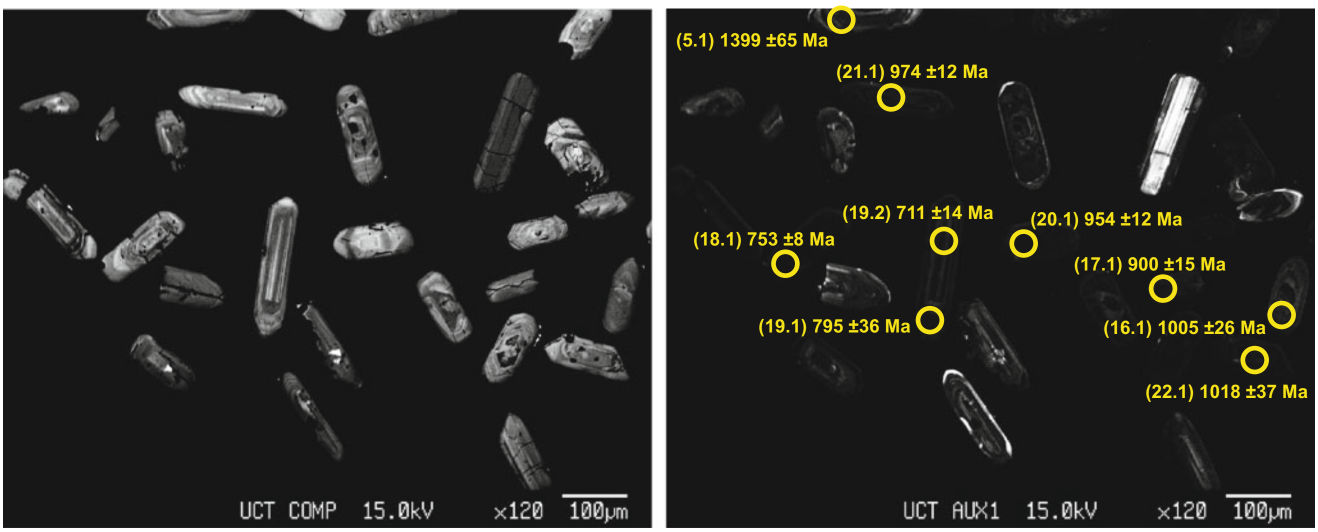


**Fig. 7.14** Example of back-scattered electron (*left* photo) and cathodoluminescence (*right* photo) images of detrital zircons from sample S2035 (the Haute Lueki Group), with location of laser spots and U-Pb results

#### 7.4.3.3 Early Neoproterozoic to Mesoproterozoic (850– 1400 Ma)

Early Neoproterozoic to Mesoproterozoic dates are abundant in all the samples (Fig. 7.12), indicating important and prolonged contributions from Kibaran-age sources to the CB. Although only in the samples from the Lukuga Group, 5 zircons dated at 1.37–1.42 Ga coincide with the Kibaran type-area along the eastern margin of the basin, recently dated at 1375 Ma (Tack et al. 2010). Most other dates are restricted between 950 and 1100 Ma (Figs. 7.12b, d). The largest potential primary sources for this 1 Ga zircon age-population are within the Oubanguides to the north, in particular the central Sahara Belt in CAR and Chad (e.g. the North African Shield; de Wit et al. 2014 in press), and on the opposite side of the Atlantic within the Brasiliano (Araguaia and Aracuai) Belts of northeastern Brazil (e.g. Dos Santos et al. 2010). These northern provenances for the CB are supported by other recent detrital zircons studies (Frimmel et al. 2006; Jelsma et al. 2011) that also found dominant 1 Ga age-populations within the upper Neoproterozoic to early Paleozoic West Congolian and Inkisi Groups along the western margin of the basin. The Pan

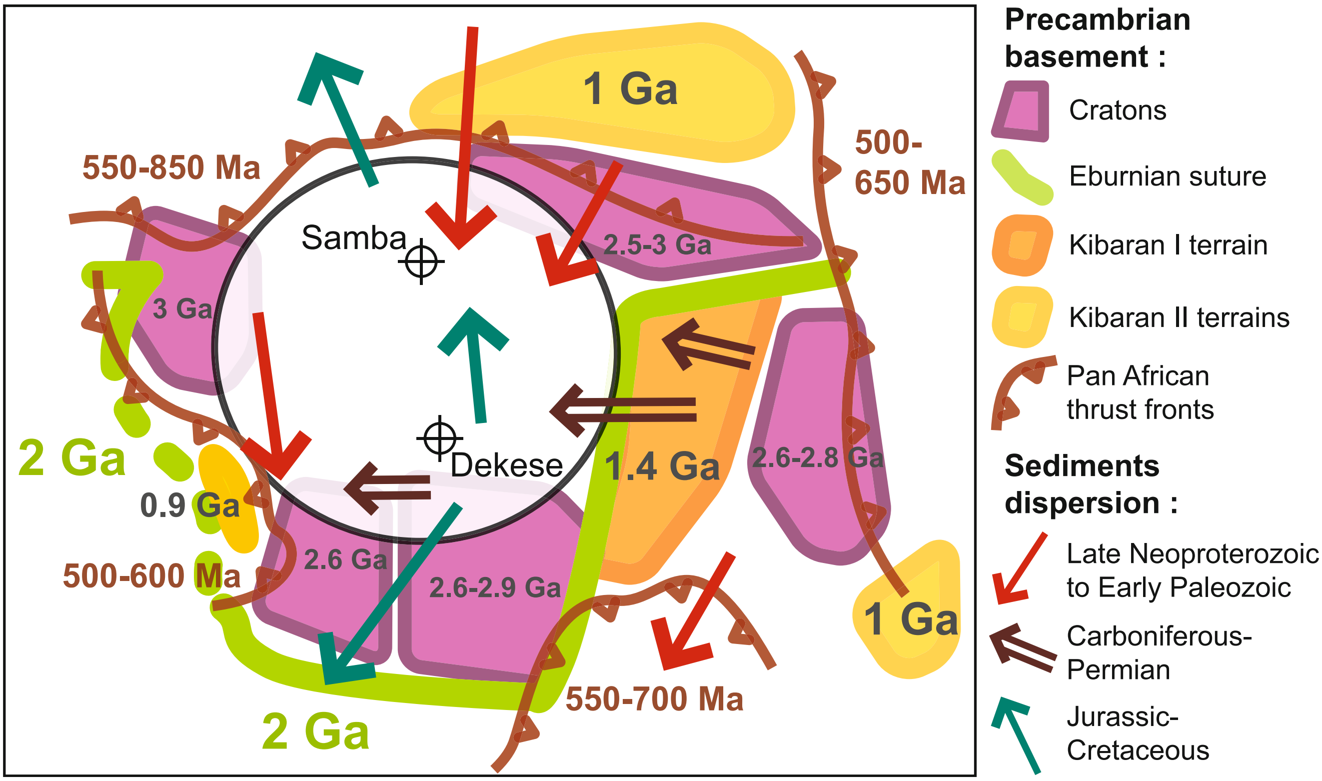


**Fig. 7.15** Simplified map of Precambrian basement ages surrounding the CB (see also Chap. 2, this Book), showing main sediment dispersal directions

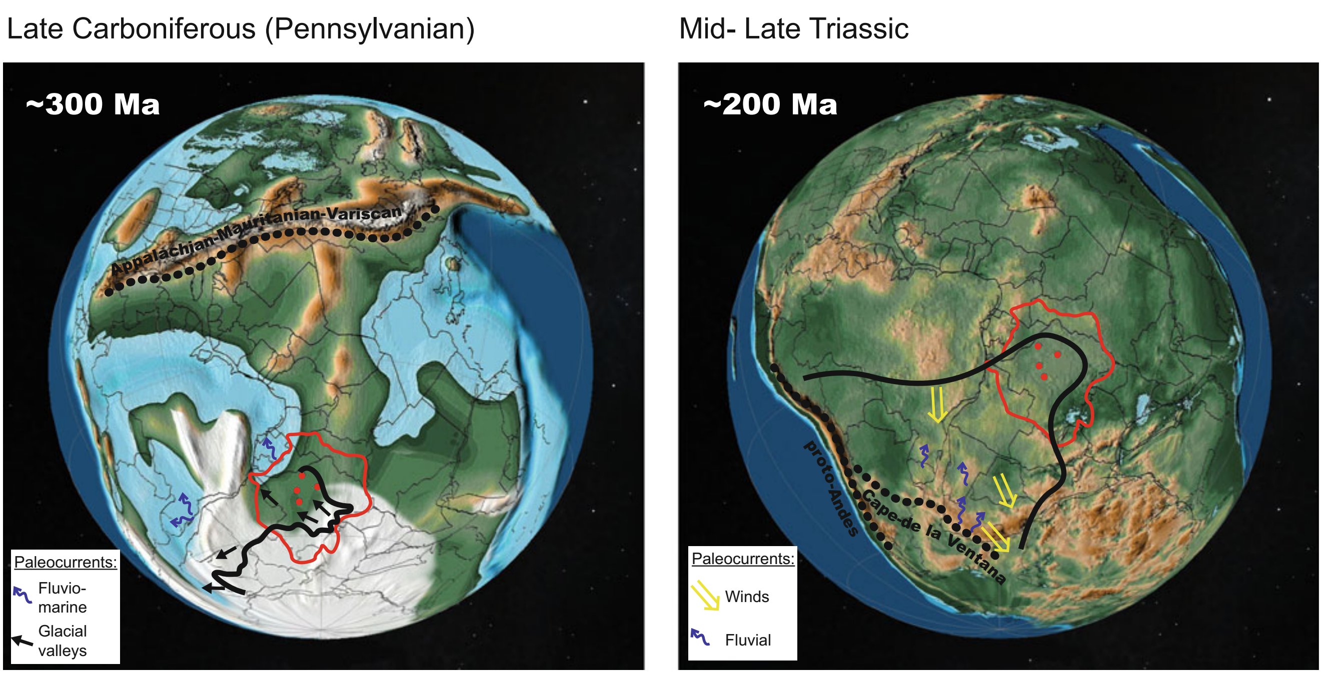


**Fig. 7.16** Schematic paleogeographic reconstructions (*left*: Late Carboniferous; *right*: Middle- Late Triassic) showing the extension of depositional sequences (*thick black line*) and paleocurrent directions (*arrows*) in central West Gondwana, superimposed on paleo-globes from Moore and Scotese (2013). *Red dots* and outline are the borehole locations and modern Congo drainage basin, respectively

African mobile belts and their overlying sedimentary cover surrounding the CB, thus could have constituted important secondary sources for the sediments in the center of the basin (Fig. 7.15).

#### 7.4.3.4 Cambrian to Late Neoproterozoic (500–850 Ma)

Cambrian to late Neoproterozoic dates are relatively abundant in all the samples (Figs. 7.12b, d). This large peak between 500 and 850 Ma indicates important Pan African contributions to the CB. However, because Pan African fold-and-thrust belts and associated molassic sequences with this age-range completely surround the basin, at this stage it is not possible to differentiate between these widely different source terrains (Fig. 7.15). Sediment dispersal directions favor Pan African sources located to the east (e.g. the Lufilian and Mozambique Belts) and to the north (e.g. the Oubanguides Belt). Also, the increase in abundance of this 500–850 Ma zircon age-population in the samples from the Lukuga Group (22 grains) to the Haute Lueki Group (36 grains) suggests progressive concentration by sediment recycling during the early Mesozoic.

**Conclusion**

The four new stratigraphic sections reconstructed from the deep boreholes drilled in the center of the CB in the 1950s and 1970s, all show at their lower part great thicknesses of conglomerates, quartzitic sandstones and red siltstones (e.g. 3 km at Mbandaka) overlying deformed Pan African carbonate rocks (Fig. 7.10). The lowermost sequences locally include dark siltstones and black shales dated by palynostratigraphy to the Carboniferous-Permian in the Dekese and Mbandaka sections (Boulouard and Calandra 1963; Colin and Jan du Chêne 1981), and attributed to the glacial-periglacial Lukuga Group. In the center of the basin, this first supersequence is between 900 and 1,600 m thick, truncated at the top by a regional erosion surface (U2), and is in turn overlain by 900–1,800 m thick red quartzitic sandstones and siltstones of the Triassic Haute-Lueki Group. The angular unconformity separating these two groups is equivalent to the main erosion surface that separates the lower and upper Karoo successions in southern Africa, and thus may be linked to large-scale deformation across the entire interior of Gondwana during the late Paleozoic Mauritanian-Variscan (ca. 275–325 Ma; Dabo et al. 2008) and Cape-de la Ventana (ca. 245–278 Ma; Newton et al. 2006) orogens along its northwestern and southern margins, respectively (Fig. 7.16; Scotese 2014). The overlying major unconformity (U3) across these Carboniferous to Triassic sequences of the CB is now re-assigned to the Jurassic, and believed to be related to the initial period of break-up of Gondwana during the opening of the Indian Ocean (see Chap. 13, this Book).

U-Pb detrital zircons geochronology from these sequences characterizes the evolution of source provenances for the CB during the late Paleozoic and early Mesozoic. In the lower diamictites of the Lukuga Group in the Dekese section, abundant detrital zircons of 1.85–2.05 Ga and subordinates of 1.37–1.42 Ga indicate largely dominant contributions from Eburnian and Kibaran sources in east Africa, as supported by the west-facing paleo-glacial valleys along the margins of the basin (Fig. 7.16). An elevated paleo-topography in east Africa during the Carboniferous-Permian is also consistent with recent thermochronology in Tanzania (Kasanzu 2014) that shows ca. ~7 km of exhumation of the Tanzanian Craton from 460 Ma to 220 Ma. In the overlying Haute Lueki Group in the Samba section, more dominant detrital zircons of 950–1100 Ma and 500–800 Ma derived from north-central Africa, as shown by the crystal shapes of the zircons that indicate limited transport (Fig. 7.14). In contrast, input from the Kibaran Belt of eastern DRC is almost absent in all these samples, suggesting that this vast region stopped acting as a main source for the CB, possibly being covered by sediments or subsided below sea level during the Mesozoic.

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