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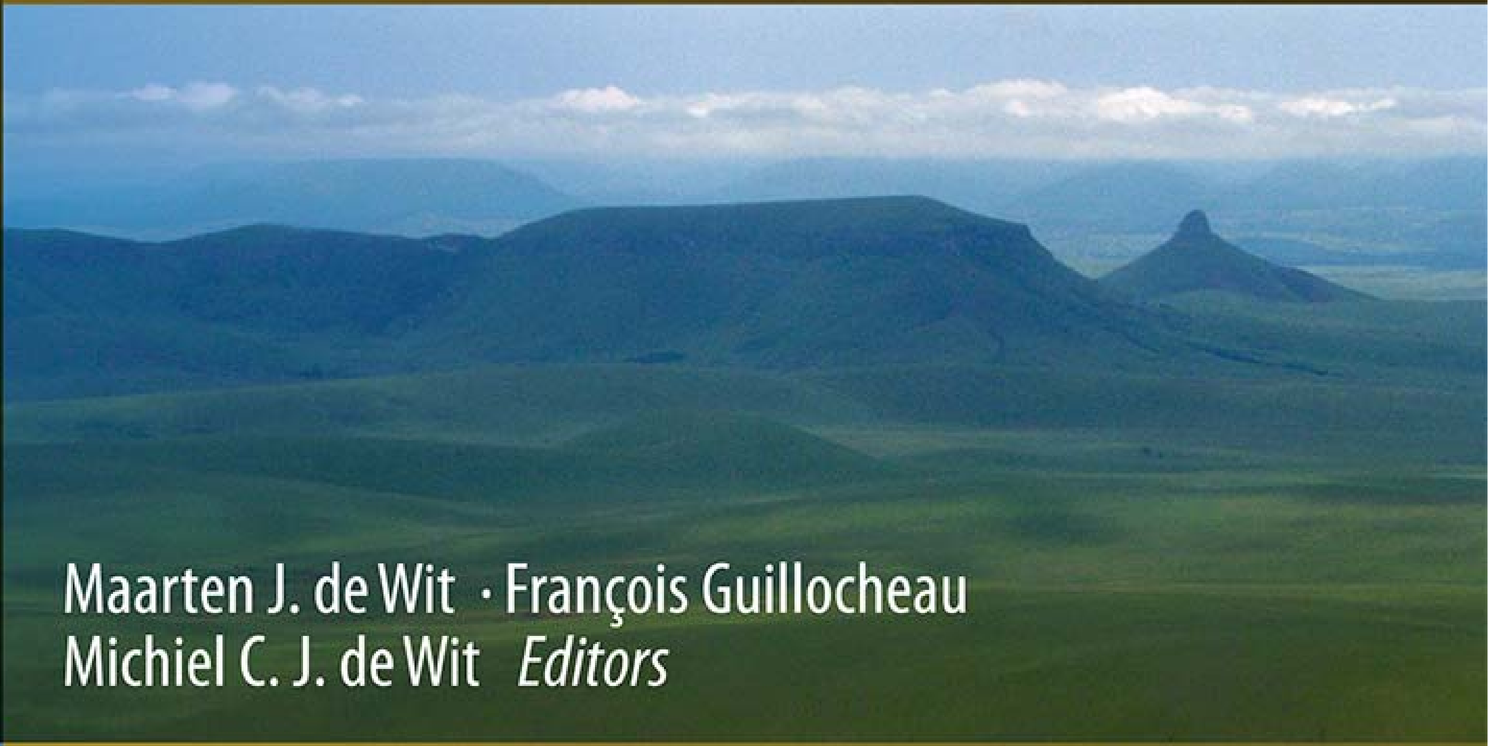

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Geology and Resource Potential of the Congo Basin

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Neoproterozoic to Lower Paleozoic Sequences of the Congo Shield: Comparisons Between the Congo and Its Peripheral Basins

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6.1 Introduction

The Congo Basin (CB) is the largest and the least explored African continental sedimentary basin. Outcrop scarcity, intense weathering and dense forest constitute obstacles to undertake direct geologically-based exploration programmes, highlighting the importance of airborne and ground-based geophysics. In the 1950s, the 'Syndicat pour l'étude géologique et minière de la Cuvette congolaise' conducted refraction and reflection seismic, gravimetric and magnetic field surveys across the central parts of the CB (Evrard 1957). During the seismic surveys, 117 refraction stations were employed in the basin interior, and 7 reflection lines were recorded along rivers (Evrard 1960). In addition, about 6,000 gravity and magnetic measurements were made with an average station spacing of 5 km along rivers and dirt roads (Jones et al. 1960). Moreover, two fully-cored stratigraphic wells down to ca. 2,000 m had been drilled in the 1950s, reaching red sandstones at the bottom, that were interpreted as pre-Carboniferous (Cahen et al. 1959, 1960).

Using these geophysical and well data, Evrard (1957, 1960) and Jones et al. (1960) first imaged the structure and extent of the CB and its subsurface geometry. The major refractors mapped provided the first regional overview of the basin subsurface structure. The CB appeared deeper than previously thought, with the possible existence of several thousand meters of sedimentary rocks beneath its upper Paleozoic–Mesozoic sedimentary sequences.

Additional geophysical surveys were subsequently conducted by various petroleum companies. Exxon-Texaco shot 2,900 km of seismic reflection profiles in 1974–1976, and Japan Oil National Corporation (JNOC) performed an aeromagnetic survey and gravity measurements around Kisangani in 1984; and two additional wells, more than 4,000 m deep, were drilled (Esso Zaire 1981a, b). The interpretation of this data was first presented in an ECL (1988) report by Petrozaïre, of which a short summary was published by Lawrence and Makazu (1988). More detailed interpretations of the seismic reflection profiles and wells were presented as synthetic stratigraphic columns and a tectonic model by Daly et al. (1992), in which early subsidence of the basin was interpreted to reflect Neoproterozoic processes of rifting and thermal relaxation, followed by two regional contractional deformation phases that inverted the subsiding basin during the early Paleozoic and the late Paleozoic. The first inversion was attributed to late stages of the Pan-African orogeny in Central Africa, and the second inversion phase to far field intraplate stresses generated at the southern margin of Gondwana during the formation of the Cape Fold Belt. Daly et al. (1992) also speculated on the possible role of evaporites in enhancing deformation process at the deepest levels of the basin. Subsequently, Kadima et al. (2011a) further constrained the interpretation of some of the seismic profiles using 2D gravity and magnetic models, and delineated heterogeneous crust beneath the sedimentary sequences of the basin consistent with the interpretation that the central part of the basin is an intracratonic rift inverted during compressional tectonics facilitated by the presence of evaporites and salt tectonics.

Despite a renewed interest over the last decade, there are still many unanswered questions regarding the nature of the crystalline basement, the Neoproterozoic and Phanerozoic stratigraphy, as well as the structure of the CB. The

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crystalline basement comprises Archean to Mesoproterozoic igneous and metamorphic rocks of the Congo Shield (see de Wit and Linol, Chap. 2, this Book). Scarce outcrops, limited geological data and stratigraphic age constraints still prevent a detailed reconstruction of the Neoproterozoic history of the CB. Nevertheless, many authors have attempted to decipher the Neoproterozoic geological evolution of Central Africa and the CB in particular (Cahen 1954; Evrard 1960; Lawrence and Makazu 1988; Daly et al 1991, 1992; Kadima 2011; Kadima et al. 2011a, b; Linol 2013; see also Chaps. 2 to 5, this Book).

Here, we re-examine the largely hidden Neoproterozoic to lower Paleozoic sequences of the CB near the centre of the Congo Shield and compare its evolution with the surrounding and partially exposed marginal sedimentary basins.

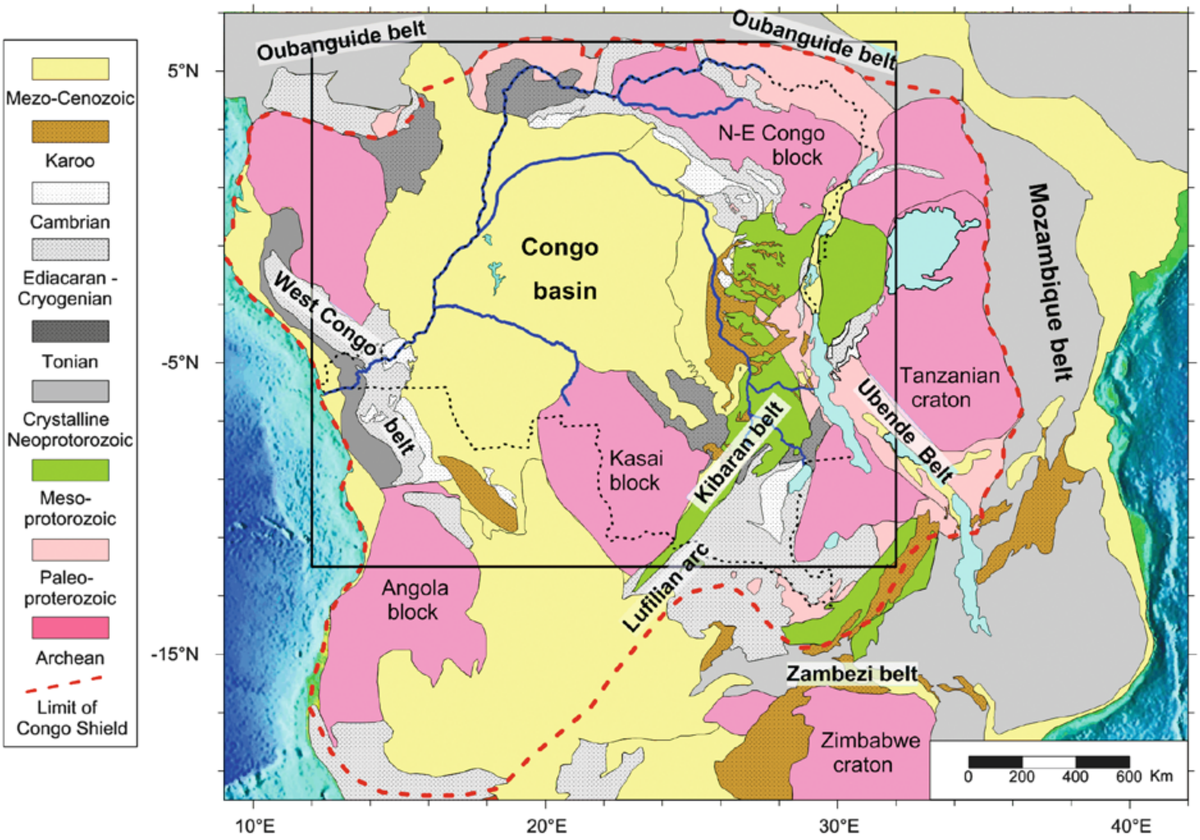
6.2 Neoproterozoic to Lower Paleozoic Sequences of the Congo Shield Flanking the CB

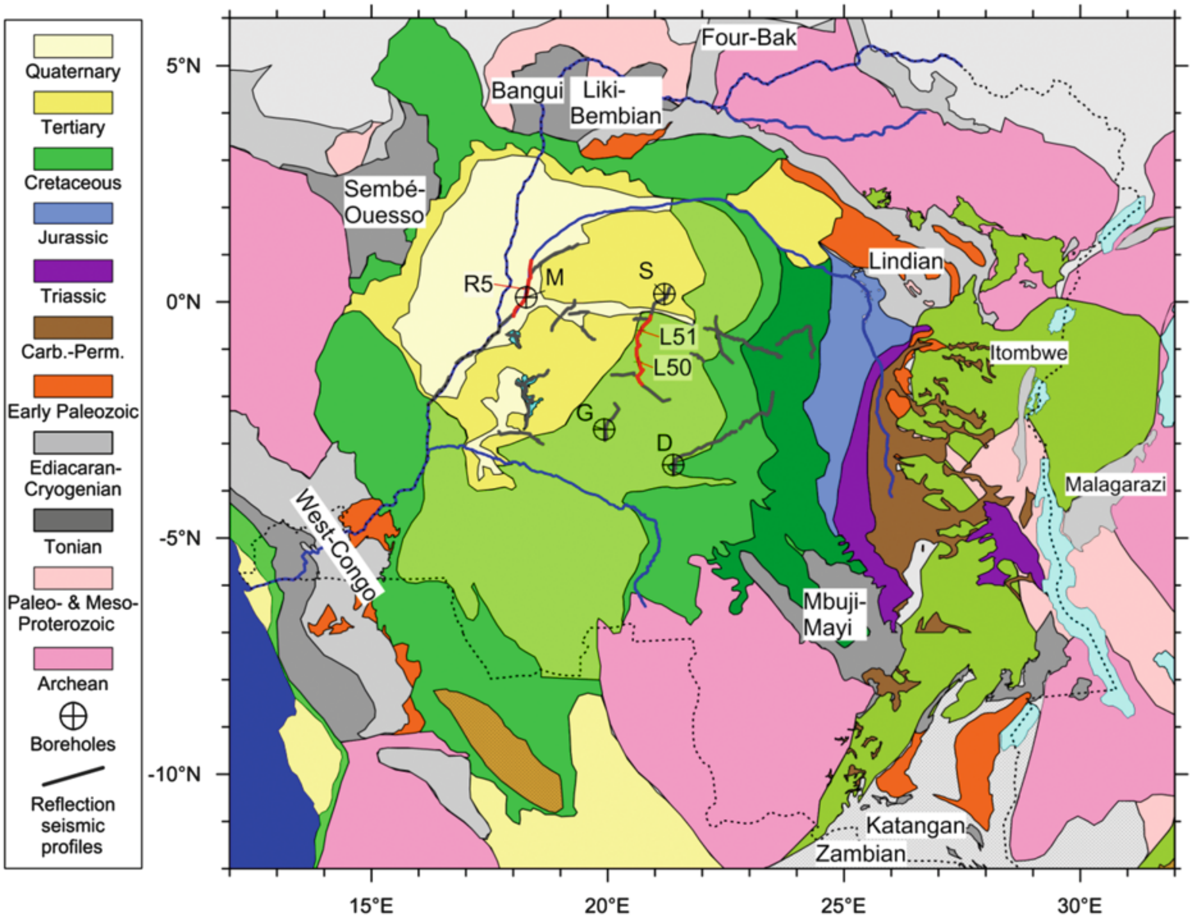
In Central Africa, the Neoproterozoic geological evolution is marked by a succession of major events initiated by the break-up of the Rodinia supercontinent and opening of rift-basins (e.g. West Congolian, Sembé-Ouesso, Mbuji-Mayi, Katanga, Zambian basins), and terminating by the amalgamation of Gondwana and the filling of associated foreland basins (e.g. de Waele et al. 2008). Traces of these events can be observed within the Congo Shield (sensu Stankiewicz and de Witt 2013) and particularly in marginal sedimentary basins surrounding the CB (Fig. 6.1a), such as the West Congo, Sembé-Ouesso, Bangui and Liki-Bembian basins to the West and Northwest; the Fouroumbala-Bakouma and Lindian basins to the North and Northeast; the Itombwe and Malagarazi-Bukoban basins to the East; the Katanga, Zambian and Mbuji-Mayi basins to the Southeast (Fig. 6.1b).

Studies based on shear-wave tomography (Crosby et al. 2010; Priestley et al. 2008; Ritsema and van Heijst 2000), admittance models (Downey and Gurnis 2009; Hartley and Allen 1994; Hartley et al. 1996; Pérez-Gussinyé et al. 2009), kimberlite data (Crosby et al. 2010; Batumike et al. 2009), subsidence modelling (Kadima et al. 2011b; Kadima 2011) and heat flow estimations (Kadima et al. 2011b; see also Lucazeau et al., Chap. 12, this Book) suggest that the CB and surrounding Lindian and Mbuji-Mayi basins are underlain by a thick mantle lithosphere (200 km or more), with an equivalent elastic thickness of ca. 100 km (for further details see Raveloson et al., Chap. 1, this Book).

Evidence of Rodinia break-up as main mechanism of formation for some of the sedimentary basins surrounding the CB is supported by the age of magmatic intrusions observed into these basins (Vicat and Vellutini 1987; Vicat et al. 1989; Key et al. 2001; Tack et al. 2001; Johnson et al. 2007; de Waele et al. 2008). A brief summary of the stratigraphy of these marginal basins is given below, in clockwise order as depicted in Fig. 6.1:

1. The West Congo basin contains rhyolites and felsic volcanoclastics dated at 950 Ma (Tack et al. 2001) and intruded by granitoids (e.g. in the West Congo Supergroup and the Sangha-Comba Aulacogen). These volcano-magmatic series have been considered to represent a continental rift sequence related to the break-up of Rodinia and the opening of the Adamastor Ocean with the deposition of passive margin sediments (Alvarez 1995a, b; Tack et al. 2001). These sequences are overlain by the Ediacaran-Cryogenian West Congo Group comprising a succession of siliciclastics interbedded with diamictites and carbonates (Frimmel et al. 2006; see also Delpomdor et al., Chap. 3, this Book).
2. The Sembé-Ouesso basin exposed in the Republic of the Congo (Congo-Brazzaville) contains sequence of schist and quartzite, overlain by a pelitic and sandstone sequence, and in turn by the Dja tillite, estimated at ca. 950 Ma (Vicat and Vellutini 1987). Dolerites intrude all these sequences; and their emplacement is interpreted to be related to crustal extension leading to basin subsidence in a failed rift (Vicat and Vellutini 1987; Vicat et al. 1989; Vicat and Pouclet 1995).
3. The Fouroumbala-Bakouma and Bangui basins in the Central African Republic (CAR), the Liki-Bembian, Lindian, Itombwe syncline in the Democratic Republic of Congo (DRC), as well as the Malagarazi-Bukoban basin in Burundi and Tanzania all have been recognized to be Neoproterozoic in age, based on limited radiometric dating and lithostratigraphic correlations (Alvarez 1995a, b, 1999; Poidevin et al. 1980/1981; Poidevin 1985, 2007; Deblond et al. 2001). The age of the Bakouma Formation was first estimated at ca. 840 ± 50 Ma (Poidevin 1996), although Alvarez (1999) obtained a whole rock Rb-Sr date for these rocks of ca. 683 ± 11 Ma. Magmatic intrusions have been documented, in particular in the Fouroumbala-Bakouma, Bangui, Itombwe and Malagarazi-Bukoban basins (Waleffe 1988; Poidevin 1976, 1979; De Paepe et al. 1991; Tack 1995; Deblond et al. 2001). Amygdaloid lava belonging to the Malagarazi Supergroup has been dated at 795 ± 7 Ma (Deblond et al. 2001). Syenite, dated at 700 ± 50 Ma, intrude sediments filling the Itombwe basin (Villeneuve 1983).
4. The Katangan and Zambian basins, now part of the Lufilian (Arc) fold-and-thrust belt, developed during two magmatic events between 880 Ma and 750 Ma (Porada 1989; Armstrong et al. 2005; Johnson et al. 2005), and were subsequently deformed during the Pan-


Mezo-Cenozoic
Karoo
Cambrian
Ediacaran - Cryogenian
Tonian
Crystalline Neoprotorozoic
Meso-protorozoic
Paleo-proterozoic
Archean
Limit of Congo Shield
5°N
-5°N
-15°N
10°E
20°E
30°E
40°E
Oubanguide belt
Oubanguide belt
N-E Congo block
Congo basin
West Congo belt
Tanzanian craton
Mozambique belt
Ubende Belt
Kasai block
Kibaran belt
Lufilian arc
Angola block
Zambezi belt
Zimbabwe craton
0 200 400 600 Km


Quaternary
Tertiary
Cretaceous
Jurassic
Triassic
Carb.-Perm.
Early Paleozoic
Ediacaran-Cryogenian
Tonian
Paleo- & Meso-Proterozoic
Archean
Boreholes
Reflection seismic profiles
5°N
0°N
-5°N
-10°N
15°E
20°E
25°E
30°E
Four-Bak
Bangui
Liki-Bembian
Sembé-Ouesso
Lindian
R5
M
S
L51
L50
G
D
Itombwe
Malagarazi
West-Congo
Mbuji-Mayi
Katangan
Zambian

African orogen, between ca. 700 Ma and ca. 530 Ma (Cailteux 1994; Hanson et al. 1994; Porada and Berhorst 2000; Key et al. 2001; De Waele et al. 2008). These basins comprise the Roan, Mwashya, Nguba and Kundelungu Groups. The Roan Group overlies the 877 ± 11 Ma Nchanga granite (Armstrong et al. 2005), and the Mwashya Group contains 765 ± 5 Ma intrusions (Key et al. 2001).

5. The Mbuji-Mayi basin is a SE–NW trending intracratonic failed-rift basin. It contains a lower clastic sequence BI and an upper carbonate sequence BII (Raucq 1957, 1970; Cahen et al. 1984; Delpomdor, et al. 2013a). The presence of dolerite intrusions and pillow lavas were taken as evidence of extensional magmatism during the deposition of the Mbuji-Mayi sediments (Raucq 1957, 1970; Cahen et al. 1984). Isotopic data from the Mbuji-Mayi carbonates and the presence of pseudomorphs of anhydrite and gypsum filling veins and fractures reflect deposition and early diagenesis in marine and evaporitic conditions (Delpomdor, et al. 2013b; see also Delpomdor et al., Chap. 4, this Book). The minimum age of sedimentation for the Mbuji-Mayi Supergroup was first estimated by amygdaloid basalts interpreted as capping the entire sequence and dated at ca. 940 Ma (Cahen et al. 1984). Delpomdor et al. (2013a) further constrained the deposition of this Group between 1174 ± 22 Ma and ca. 800 Ma; and the carbonate BII Group is now dated at 760–820 Ma by Carbon and Strontium chemical stratigraphy (Delpomdor et al., Chap. 4, this Book) and the sliciclastic BI Group is either older than 880 Ma or aged between 880 Ma and 850 Ma. Following this second hypothesis, the Mbuji-Mayi Supergroup would be coeval with the Roan Group in the Katanga and Zambian basins, reflecting a similar early Neoproterozoic extension event.

For example, in the West-Congo basin, the Schisto-Calcaire Subgroup overlies the Haut Shiloango Subgroup and is overlain by the Mpioka Subgroup. The Haut Shiloango Subgroup comprises predominantly carbonates, with increasing siliciclastics upwards (Delpomdor et al. 2014; and Chap. 4, this Book). The Mpioka Subgroup consists of up to 1,000 m of molasse-like sequences comprising conglomerates, sandstones and argillites (Alvarez 1995a, b; Tack et al. 2001; Frimmel et al. 2006). Similarly, in the Bangui basin, the basal Kembe sequence of conglomerates is overlain by the Bimbo sandstones and the Bangui carbonates. Here, no clastic sequence is observed above this carbonate sequence (Poidevin 1976).

A similar succession is observed in the Fouroumbala-Bakouma basin (Alvarez 1995a, b; Tait et al. 2011). In the Lindian basin, the Ituri Group consists of a basal clastic sequence containing conglomerates and sandstones, overlain by thick oolitic limestones and dolomites. Above it, the Lokoma and Aruwimi Groups are predominantly clastic (Verbeek 1970; Poidevin 2007). In both the Katangan and Zambian basins, the Roan Group (880–750 Ma) consists of a basal conglomerate, siliciclastics and carbonates (mainly dolomites and dolomitic shales) that unconformably overly Mesoproterozoic Kibaran formations (Cailteux et al. 2005; Batumike et al. 2006; El Desouky et al. 2008). The Roan Group is overlain by the predominantly clastic and volcano-sedimentary rocks of the Mwashya the Nguba Groups (750–620 Ma). The latter contain a basal tillite known as the "Grand Conglomerat" (Lepersonne 1974), overlain by a thick carbonate sequence including limestones, dolomites, shales, dolomitic shales and interbbeded silts and sandstones (Cailteux et al. 2005; Batumike et al. 2007). The overlying Kundelungu molasses-like sequence (620–570 Ma) starts with a second glacial horizon, known as "Petit Conglomerat" (Lepersonne 1974).

6.2.1 Neoproterozoic Siliciclastic and Carbonate Sequences

The Neoproterozoic basins surrounding the CB have consistent (similar) stratigraphic successions. In most of them, a carbonate unit, of variable thickness, overlies a basal siliciclastic sequence comprising silts, sandstones and conglomerates. The Neoproterozoic carbonates are in turn overlain by relatively thick and persistent siliciclastic sequences.

6.2.2 RedBeds and the Transition Between the Neoproterozoic and Paleozoic

Throughout Central Africa, the transition between the upper Neoproterozoic and the earliest Paleozoic sedimentary sequences is poorly constrained because the transition sequences are non-fossiliferous siliciclastic redbeds. Throughout the CB and its surrounding basins, relatively thick sequences of lithologically similar red sandstones (known as the 'Redbeds') have long been correlated and

Fig. 6.1 (Continued) (**a**) Geological setting of the Congo Shield with the Congo Basin in its center, surrounded by Archean cratonic blocks and Proterozoic mobile belts. *Rectangle* shows contour of (**b**). (**b**) Geological map of the Congo basin and surrounding marginal Neoproterozoic basins with location of the 2 stratigraphic wells (Samba and Dekese) and the two exploration wells (Mbandaka-1 and Dekese-1), indicated by their *initials* assigned to the late Precambrian (Cahen et al. 1960; Verbeek 1970; Lepersonne 1974), although some researchers recognized parts could also be early Paleozoic in age (Evrard 1957). Subsequently many authors have tried to define the Neoproterozoic-Paleozoic transition in the basins surrounding the CB on the basis rather of structural criteria in Katanga and West Congo; and on the basis of lithological correlations with the Lindian Supergroup (Kampunzu and Cailteux 1999; Porada and Berhorst 2000; Master et al. 2005; Tack et al. 2008; Tait et al. 2011).

In West-Congo and Katanga, where these Redbeds occur along the tectonic fronts of the West-Congo and Lufilian fold belts, and from there extend towards the CB into their foreland, structural relations with reference to a supra-regional late Pan-African unconformity have been used to distinguish the red sandstones as both pre- and post-dating Pan-African deformation. In the West-Congo belt, for example, the Pan-African deformation has been dated at 566 ± 42 Ma, the age of metamorphism of a dolerite sill that intrudes the Haut Shiloango Subgroup and the Inkisi Subgroup redbeds (Alvarez 1999; Tack et al. 2001; Frimmel et al. 2006). The Inkisi Subgroup is therefore considered as of latest Neoproterozoic to early Paleozoic age (Alvarez et al. 1995c; Tack et al. 2008; Tait et al. 2011). Recently, Monié et al. (2012) determined that the West Congo belt of Angola underwent two main deformation events of amphibolite grade at c. 540 and 490 Ma, followed by tectonically assisted exhumation.

Similarly, in the Katanga basin, the sub-horizontal siliciclastic sequences of the Biano (Plateaux) Subgroup (uppermost subgroup of the Kudelungu Group) discordantly overlie the folded Katanga units and are considered therefore to be post Pan-African in age (Batumike et al. 2007; Kampunzu and Cailteux 1999). The Lufilian Arc formed during collision between the Congo and Kalahari Shields between 650 and 530 Ma, with deformation peaking at ca. 550 Ma (Porada 1989; Hanson et al. 1993; Kampunzu and Cailteux 1999; Porada and Berhorst 2000; John et al. 2004; Frimmel et al. 2006). Detrital muscovites from the Biano Subgroup have a maximum Ar/Ar age of 573 ± 5 Ma at the top of the Katanga Supergroup (Master et al. 2005), while the minimum age of the Biano Subgroup is estimated as younger than 540 Ma (Kampunzu and Cailteux 1999). This suggests that at least some of the Biano sequences may have been deposited during the Cambrian (Kipata 2013).

In the sub-horizontal intracratonic Lindian Supergroup along the northern margin of the CB, no clear angular discordance has been observed within the Aruwimi Group, but the Banalia red sandstones that form the upper part of this group, have been correlated lithostratigraphically with the Inkisi Group in West-Congo and the Biano (Plateaux) Subgroup in Katanga (Alvarez et al. 1995; Tack et al. 2008; Tait et al. 2011), but there are no direct age constraints.

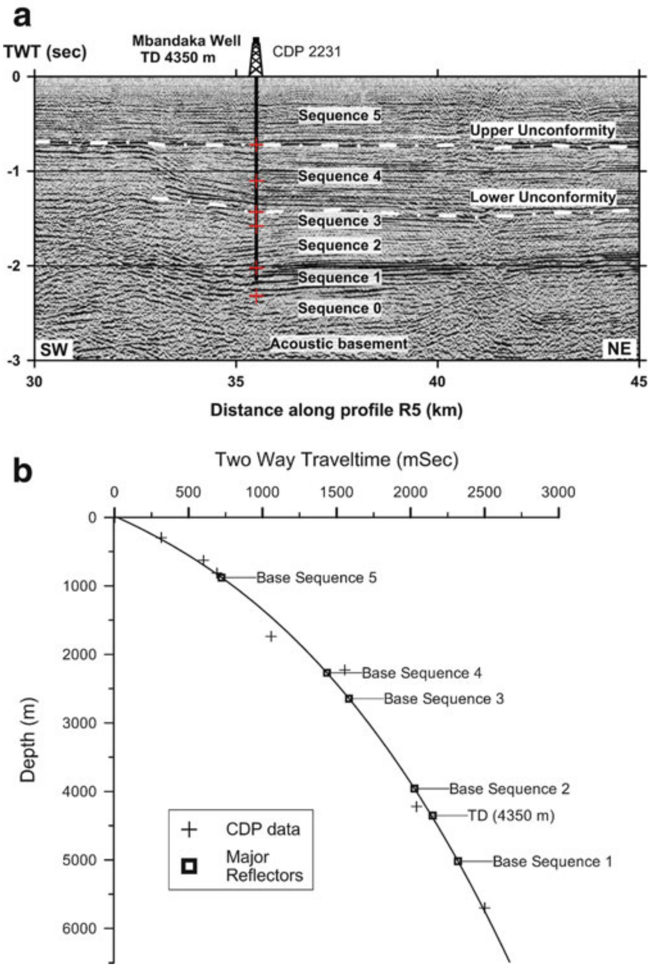


Fig. 6.2 (**a**) Seismic-stratigraphy of sequence on a section of seismic profile R5, showing six depositional sequences, two unconformities and the calibrated trace of Mbandaka-1 well as identified in this chapter. TWT: Two Way Travel-time (TWT in seconds). *Vertical black line*: position of the well, *red crosses*: base of the seismic sequences (corresponding depth in Table 6.2a). CDP 2231: Common Depth Point location. (**b**) Time–Depth curve obtained from the CDP location 2231 along line R05, near the Mbandaka-1 projected trace well. The curve shows the bottom limit of the different seismic sequences and the well TD (4,350 m). Crosses: CDP data from Table 6.1a. The depth–time curve was constructed by a polynomial interpolation of the CDP data. Empty squares: depth–time plot of the base of the seismic sequences from data of Table 6.2a

Clearly throughout the Congo Shield, robust correlations between RedBeds sequences require more precise chronostratigraphy.

6.3 Structure and Stratigraphy of the Deep CB Based on Geophysics and Well Data

Since most of the CB is not accessible to direct observations, geophysical investigations can complement the surface geology observations described above. Here we summarise interpretations of the seismic and gravity data to further unravel the early history of the CB.

Whilst a distinct seismic reflector recognized below the CB has been interpreted to record Pan-African orogenesis (Daly et al. 1991, 1992; Kadima et al. 2011a), it only locally resolves a tectonic unconformity (for example on lines L50 and L51 in the centre of the basin; Figs. 6.3 and 6.4: marked as 'Lower unconformity'). More often the reflector marks a conformable contact (see for example, line R5 calibrated against the Mbandaka-1 well; Fig. 6.2a).

6.3.1 Well Data

The original lithostratigraphic scheme of the central CB was established from logging the two fully cored stratigraphic wells: Samba and Dekese (Cahen et al 1959, 1960) and the two exploration wells: Mbandaka-1 and Gilson-1 (Esso Zaire 1981a, b) (location on Fig. 6.1). The Jurassic to Cretaceous sequences that form the uppermost 700–1,200 m are relatively well described and dated by biostratigraphy (Colin 1994; Linol 2013; Linol et al., Chap. 8, this Book). Below, the Permo-Carboniferous sequences of the Lukuga Group were recognized in the Dekese well on the basis of their fossil plants and spores, and their glacial to peri-glacial characteristics. These were not encountered in the Samba well but suspected in the Mbandaka-1 and Gilson-1 wells. In the latter two deeper wells, these sequences overlie siliclastics with dolomites (some with stromatolites) assigned to the Neoproterozoic, although the transition between the Precambrian and Paleozoic is poorly defined (see detailed lithostratigraphic subdivision of the four wells in Linol et al., Chap. 7, this Book). The Mbandaka-1 borehole stops at the depth of −4,350 m in a soft basement, interpreted to be halite (Esso Zaire 1981a).

6.3.2 Velocity Structure Based on Seismic Refraction Data

Evrard (1957) defined for the first time the P-wave velocity structure of the CB, based on the results of a refraction seismic survey calibrated with surface and well data at Samba and Dekese. Whilst Evrard (1957) stressed that this velocity structure is based on the physical characteristics of the sedimentary rocks and does not directly reflect the stratigraphy, the following synthesis seems robust: P-wave velocities <3,600 m s^{-1} characterize the Mesozoic-Cenozoic sequences whilst velocities of ca. 3,900 m s^{-1} are typical for the middle to upper Paleozoic sequences. Higher velocities, between 4,200 and 4,600 m s^{-1}, likely represent the late Neoproterozoic to lower Paleozoic RedBeds, whilst velocities > 5,000 m s^{-1} should represent the Neoproterozoic or older sediments and possibly crystalline basement.

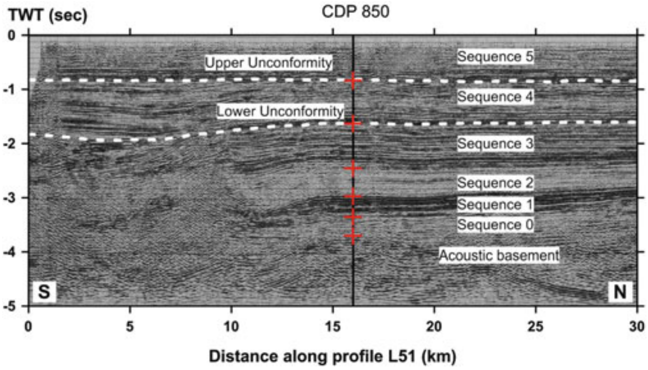


Fig. 6.3 Seismic stratigraphy of sequences identified on a section of profile L51 in the CB and linked further north to the Samba well (Fig. 6.1b) and two major unconformities as interpreted in this chapter. The *first four* sequences beneath the lower unconformity are deformed on the *left* (SW) side of the profile. *TWT* Two Way Travel-time (in seconds). *Vertical black line*: position of CDP 850, *red crosses*: base of the seismic sequences (corresponding depth in Table 6.2b)

6.3.3 Seismic-Stratigraphic Sequences

Using the seismic profiles acquired by Exxon-Texaco in 1974–1976 (location on Fig. 6.1), ECL (1988) and Daly et al. (1992) distinguished six seismic-stratigraphic sequences (or "Supersequences") above the acoustic crystalline basement, each bounded by regional unconformities. These sequences are re-described below (using the same numbering as in Daly et al. 1992) with reference to the seismic profile R5 shot along the Congo River and passing close to the Mbandaka-1 well (Figs. 6.1b, 2a). They are also illustrated on the land seismic profile L51 whose northern extremity approaches the Samba well (Figs. 6.1b, 3).

On the R5 profile (Fig. 6.2a), the depth-time curve is presented for CDP (Common Depth Point) location 2,231, measured closest to the Mbandaka-1 well (Fig. 6.2b). The depth-time curve was constructed by a polynomial interpolation of the CDP data (Table 6.1a). This allowed calculating the depth of the base of the different seismic-stratigraphic sequences and their thicknesses, as identified on the seismic line R5 (Table 6.2a). For reference, the bottom (TD) of the Mbandaka-1 well at 4,350 m deep correspond to a TWT time of 2,139 ms. Similarly, the depth to the base of the sequences identified on Line L51 have been calibrated for CDP 850 (Fig. 6.3, Tables 6.1a and 6.2b).

Except for the uppermost sequence (5), the ages of all sequences is poorly defined. Two major unconformities are identified and traced in most of the seismic profiles

Table 6.1 CPD data

(a) For location 2231 along the line R5, close to the Mbandaka-1 well									
Times (ms)	1	316	601	691	1,058	1,555	2,041	2,500	5,000
VRMS (m/s)	1,756	1,859	2,085	2,345	3,282	3,865	4,133	4,555	8,000
Depth (m)	1	294	623	786	1,621	2,824	4,023	5,422	15,000
(b) Location 850 along line R51									
Times (ms)	0	625	750	1,050	1,450	1,850	2,225	2,975	5,000
VRMS (m/s)	2,000	2,500	2,690	3,145	3,565	4,075	4,480	4,950	6,000
Depth (m)	0	701	999	1,609	2,506	3,615	4,758	7,059	14,422

Table 6.2 Depth for the base of seismic sequences and their thickness, obtained after calibration using the CDP data

(a) Location 2231 along the line R5, close to the Mbandaka-1 well						
Seismic sequences	5	4	3	2	1	0
Depth (m)	877	2,270	2,844	3,960	4,350	[a]
Thickness (m)	877	1,393	370	1,320	390	[a]
(b) Location 850 along line R51						
Seismic sequences	5	4	3	2	1	0
Depth (m)	1,120	2,990	5,410	7,070	8,290	9,400
Thickness (m)	1,120	1,770	2,420	1,660	1,220	1,210

[a] Base of the sequence No defined

(relatively distant one from another). However their age control is also poor (especially for the lower one) and it is possible that there are more than 2 regional unconformities (e.g. Daly et al. 1992 identified 6 unconformities).

6.3.3.1 Sequence 0

Along several profiles, a reflection-free seismic pattern that corresponds to the acoustic basement is interpreted to represents crystalline basement. The latter is overlain by a low-amplitude, discontinuous and transparent seismic patterns forming the first sequence (Sequence 0 of Daly et al. 1992). The reflectors diverge towards the centre of the CB, suggesting tilting during deposition; and the sequence is thicker in the centre of the basin than at its border. Sequence 0 is apparently discontinuous, with rapid variations in thickness and its base generally is not well-imaged. Sequence 0 was not penetrated by any cored wells. It could represent siliciclastic sediments (essentially conglomeratic) if correlated with the Liki-Bembian Group outcropping to the NW of the basin (e.g. Daly et al. 1992) and may thus represents the basal Precambrian sedimentary unit of the CB. Alternatively, it may also be correlated with the lower Neoproterozoic clastic sequence (BI) of the Mbuji-Mayi basin (Delpomdor et al. 2013a, b; and Chap. 4, this Book) and the Roan Group of the Katangan and Zambian basins.

The base of sequence 0 is not identified in the R05 seismic profile, but suspected in profile L51, at ~ TWT 3,710 ms, which is calibrated using the CDP 850 data at ~9,400 m depth, for a thickness of ~ 1,100 m (Fig. 6.3; Tables 6.2a, b).

6.3.3.2 Sequence 1

Sequence 1 has a layered seismic pattern characterized by highly continuous and divergent reflectors. In the Mbandaka-1 well its top occurs at ca. 3,960 m, and its bottom at 4,350 m. From this bottom upward to 4,133 m depth, the sequence is represented by a 217 m thick succession of dark-grey calcareous silty shales that grade into argillaceous and dolomitic limestones, with interbedded salt crystals and sparse anhydrite at the base (Esso Zaire 1981a). In the Gilson-1 well, it is represented between 4,503 m depth and the bottom of the well (4,665 m) by alternating beds of sandstone, siltstone, shale and dolomite, with massive dolomite at the base (Esso Zaire 1981b). Sequence 1 is correlated with the Ituri carbonates of the Lindian Supergroup of Verbeek (1970) and represents the M9 sequence of Linol (2013) in the Mbandaka-1 well, and the G10 sequence of Linol (2013) in the Gilson-1 well. It could possibly be correlated also with the carbonate sequence (BII) of the Mbuji-Mayi basin (Delpomdor et al. 2013a, b). Using the CDP 2231 data, its thickness at the position of the Mbandaka-1 well would be ~ 670 m. In profile L51, at CDP 850, Sequence 1 is ~1,220 m thick with its base at a depth of ~ 8,290 m (Fig. 6.3, Table 6.2b).

6.3.3.3 Sequence 2

A second transparent seismic pattern with discontinuous reflectors and one or two strong to medium continuous reflectors in the middle overlies Sequence 1. In the R5 profile (Fig. 6.2a, b; Table 6.2b), it corresponds to an interval

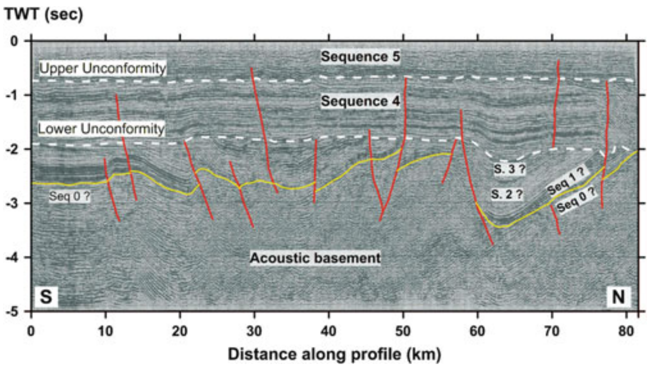


Fig. 6.4 Seismic stratigraphy and structural interpretation of N–S seismic line L50 in the center (Fig. 6.1b). The lower unconformity has been deformed during or after deposition of Sequence 5 by reactivation of underlying structures. *Yellow line*: folded and faulted reflector at the base of strongly reflecting sequence 2. *TWT* Two Way Traveltime (Seconds)

between 2,644 m and 3,960 m depth (1,316 m thick). It also broadly corresponds to conglomeratic and sandstone sequences M9 and M8 of Linol (2013). The transparent character is well seen in the seismic profile R51 (Fig. 6.3), where at CDP 850, it is ca. 1,660 m thick and its base is at ca. 7,070 m deep (Table 6.2b).

6.3.3.4 Sequence 3

Sequence 3 has a banded seismic pattern characterized by slightly divergent and strongly to moderately continuous reflectors. An angular unconformity observed along the deformed part of the basin constitutes the upper boundary of the sequence, which defines the lower major regional unconformity and can be detected on most of the seismic profiles (Daly et al. 1992; Kadima 2011; Kadima et al. 2011a, b). The angular character of this unconformity is well defined in the southern part of profile L51 (Fig. 6.3), and in the central part of profile L50 (Fig. 6.4). In profile R5 (Fig. 6.2a), it appears as a conformable contact and is therefore more difficult to identify. In the R5 profile, at the location of the Mbandaka-1 well, Sequence 3 appears between ~2,270 and ~2,640 m deep (Table 6.2) and is correlated in the Mbandaka-1 well with the red-orange conglomerates of the M7 sequence of Linol (2013). This sequence is observed in line L51 at the position of CDP 850, between ~5,410 and ~2,990 m (~2,420 m thick; Table 6.2b). We tentatively correlate this Sequence 3, together with the underlying Sequence 2, with similar (predominantly clastic) sequences in the marginal basins: the molassic Mpioka Group in West Congo (Frimmel et al. 2006), the predominatly clastic Kundelungu and Nguba Groups in the Katanga basin (Cailteux et al. 2007), and the dominantly clastic Aruwimi Group in the Lindian basin (Verbeek 1970).

6.3.3.5 Sequence 4

Overlying the lower regional unconformity, a parallel to subparallel seismic pattern marked by moderate to low continuous reflectors constitutes the fifth sequence (e.g. Sequence 4 of Daly et al. 1992). Its upper boundary is another angular unconformity that constitutes the second (or upper) regional unconformity in the CB. Well logs show that Sequence 4 is mostly siliciclastic, comprising red sandstones and conglomerates. According to the interpretation of seismic profile R5 (Fig. 6.2a), this sequence is 1,390 m thick in the region of the Mbandaka-1 well, between depths ca. 877 m and ca. 2,270 m. It corresponds to the M5 and M6 sequences of Linol (2013, and assigned to the Triassic). On CDP 850 along line 51, it is ca. 1,870 m thick, between ca. 1,120 m and ca. 2,990 m deep.

6.3.3.6 Sequence 5

The sixth and youngest seismic sequence (Sequence 5) consists of parallel highly continuous reflectors grading upwards to wavy moderate to strong reflectors. The lower boundary of this sequence corresponds to the upper regional unconformity as defined above. Well logs and outcrop data show that it contains essentially continental clastic formations ranging in age from the Late Jurassic to the Neogene. It appears undeformed on the seismic profiles and has a relatively constant thickness over the entire CB: 715 m at Dekese (Cahen et al. 1960), 1,167 m at Samba (Cahen et al. 1959), 844 m at Mbandaka and 998 m at Gilson (Esso Zaire 1981a; Linol 2013), and ~1,120 m thick along line L51 at CDP 850.

To directly compare their seismic-stratigraphic interpretations of the CB, Kadima et al. (2011a) regroup the first four sequences of Daly et al. (1992) into a lower seismic unit (Unit A), contained beneath the lower major unconformity. This Unit A is locally affected by tectonic deformation. By correlation with the depocenters surrounding the CB and considering that this lower unconformity could represent the end of Pan-African deformation, the seismic Unit A likely represents the equivalent the Neoproterozoic sedimentary sequences flanking the CB. Sequence 4, which is bound between the two regional unconformities, is named seismic Unit B, and possibly represents the Paleozoic and early Mesozoic (e.g. Triassic; see below). In this scheme, the uppermost seismic Unit C would represent the Jurassic-Cretaceous and Cenozoic.

6.3.4 Tectonism

The Neoproterozic sequences of the seismic Unit A as defined above have been affected by Pan-African deformation. Some of those structures apparently have been reactivated also by late Paleozoic-early Mesozoic deformations. In contrast, the lower-middle Paleozoic red sandstones at the base of Unit B, together with the overlying Carboniferous-Permian diamictites and black shales, have been deformed only by the late Paleozoic-early Mesozoic deformation. This is well illustrated by the N-trending seismic profile L50 in the centre of the basin (Fig. 6.4) by structures such as flexures, anticlines, synclines and thrust faults, although it would be difficult to distinguish these from syn-depositional features related to slumping and glacial processes, or even salt tectonics. The first deformation event occurred prior to the deposition Sequence 4 and the second affects it, mainly by reactivating the structures underlying the lower unconformity. Each deformation event is characterized by an erosional phase followed by renewed sedimentation with by top-lap structures. These deformational events are interpreted as representing intraplate compressional tectonic episodes related to far-field tectonic stresses generated by Pan African collisional tectonics flanking the margin of the Congo Shield for the first event, and at the margin of Gondwana (during the formation of the Cape Fold Belt at ca. 250 Ma) for the second one (e.g. Daly et al. 1992; Kadima et al. 2011a; Kipata et al. 2013. However, if the Sequence 4 also includes the Triassic, then the second deformation would be post-Triassic and therefore cannot be related to the Cape Fold Belt and would require a different interpretation of the far field stresses (Linol 2013; see also Linol et al., Chap. 11, this Book).

6.3.5 Gravity Anomalies and Modelling

The CB is associated with a large-scale and pronounced negative free-air gravity anomaly (Jones et al. 1960; Sandwell and Smith 1997; Tapley et al. 2005). Initiation of the CB is frequently related to the development of a NW–SE Neoproterozoic rift and a large part of its subsequent subsidence to post-rift thermal relaxation (e.g. Kadima et al. 2011a, b; Buiter et al. 2012).

The large scale and amplitude of the gravity anomaly has led various researchers of the CB to propose very different geodynamic models to account for subsidence of the CB. Hartley and Allen (1994) and Hartley et al. (1996), for example, suggested the negative Bouguer gravity could be due to the combined effect of lower density sediments in the basin and higher density material in the lithospheric mantle to isostatically compensate for the sediments; and indeed, Downey and Gurnis (2009) show numerically that the topography and negative free-air gravity data over the basin can be explained by a high-density body within the deeper lithosphere.

By contrast, Heine et al. (2008), suggested that subsidence might be due to dynamic topography, consistent with Sahagian (1993) and Burke and Gunnell (2008), who prefer models in which the CB acquired its modern shape through mantle (plume) driven uplift of swells surrounding the basin.

Others prefer a model in which recent subsidence of the CB is controlled by a late phase of the ca. 700 Ma post-rift thermal subsidence following the Neoproterozoic extension (e.g. Armitage and Allen 2010; Crosby et al. 2010; Kadima et al. 2011b), while Buiter et al. (2012) suggests that the observed negative gravity anomaly across the CB is mainly due to the thick (up to 9 km) sedimentary units in the basin, and that the sub-lithospheric mantle structures did not apparently play a role in the recent subsidence of the basin.

To further test a simple long lived thermal history for the CB, Kadima et al. (2011b) backstripped the effects of the CB sediments and noted a residual NW–SE positive and narrow gravity anomaly across the central CB, which they interpreted as the remaining crustal thinning associated with the Neoproterozoic rift that initiated the CB. The paleo-rift is aligned along the Mbandaka-1 and Dekese positive Bouguer anomalies of Jones et al. (1960) and Kadima et al. (2011a). Assuming that isostasy is governed by crustal necking and flexural response to sediment loads, Kadima et al. (2011b) obtained a best fit to the residual gravity with a necking depth of 10 km and an equivalent lithospheric elastic thickness of 100 km. Consequently, the linear anomaly is interpreted as an old tectono-thermal heritage of the initial Neoproterozoic rifting, when denser mantle associated with Moho uplift invaded the necking zone and has remained in place ever since (Kadima et al. 2011b). 2D coupled gravity and magnetic models were constructed across this elongated NW-trending positive residual anomaly, along the seismic lines constrained by well data, to test the hypothesis for a rifting process with extensional magmatism activity prior to the basin formation (Kadima et al. 2011a). The main results are as follows:

- Modeling of two SW–NE profiles, one along the Congo River and passing close to the Mbandaka-1 well and one passing through the Dekese well is consistent with a lateral change in basement density along the trend of the profile, suggesting that the elongate positive NE-tending residual gravity anomaly zone could correspond to a deep crustal discontinuity injected by mafic magma during the Neoproterozoic rifting.
- The modelling is also consistent with (but does not prove) the presence of evaporite sequences in some of the deeper units in lateral continuity with evaporite showings

observed at the bottom of the Mbandaka-1 and Gilson-1 wells. The modelled low susceptibility values of some layers suggest that they could contain a significant proportion of salt.
- The poorly defined seismic facies that led to the previous interpretations of crystalline basement uplift is shown to be also consistent with paleo-salt tectonics.

6.4 Discussion

The Neoproterozoic period in Central Africa was marked by crustal extension with the opening of rift basins during the initial development of the CB near the centre of the Congo Shield. This was accompanied by the formation and preservation of Neoproterozoic basins surrounding the CB. Lithostratigraphic, structural, and paleo-environmental similarities have been established between all these basins (Tait et al. 2011; Delpomdor 2013; Delpomdor et al., Chap. 4, this Book). The sediments were subsequently affected by compressional tectonics related to the Pan African and late Paleozoic-early Mesozoic orogens.

The data discussed here suggest to us rather that the Neoproterozoic CB was initiated during an intracratonic rifting process, possibly related to the break-up of the Rodinia Supercontinent. Such extensional setting may also have initiated the development of the other Neoproterozoic basins now preserved along the periphery of the Congo Shield. Mafic magmatism associated with this regional rifting event is observed in the West Congo, Sembé-Ouesso, Bangui, Fouroumbala-Bakouma, Itombwe, Malagarazi-Bukoban, Roan, Kundelungu and Mbuji-Mayi basins (Tack et al. 2001, 2010; Vicat et al. 1989; Hanson et al. 1994; Johnson et al. 2005; Key et al. 2001; Kampunzu and Cailteux 1999; Batumike et al. 2009; Delpomdor et al. 2013b). Within the CB, there is no evidence to confirm or exclude similar magmatic activity, but 2-D modelling suggests that a linear NW-SE positive residual gravity anomaly in the centre of the basin may be associated with mafic intrusions into the crustal basement. Both Evrard (1957) and Kadima et al. (2011a, b) attributed the short wavelength gravity anomalies observed near Dekese and Mbandaka-1 to such intrusions into the upper crust.

The lithostratigraphic successions in all the Neoproterozoic basins developed across the Congo Shield show first-order similarities, with in their lower parts carbonate-rich sediments overlain by siliciclastic sequences that include tillites (for more details see Delpomdor et al., Chap. 4, and de Wit and Linol, Chap. 2, this Book). In most of the peripheral basins, the carbonate units overlie a basal conglomeratic sequence. As shown by the deep well logs (Esso Zaire 1981a, b) and previous seismic analysis, the deepest part of the CB may contain similar units. A massive carbonate formation with evaporite showings (the “carbonate-evaporite” sequence of ECL 1988; Lawrence and Makazu 1988; Daly et al. 1992), was reported from the lower Mbandaka-1 well and defined as Sequence 1 (670–1,200 thick). The carbonates are considered as late Neoproterozoic, Ediacaran-Cryogenian (e.g. Daly et al. 1992; Kadima et al. 2011a; Linol 2013; Delpomdor, et al., Chap. 4, this Book) by lithostratigraphic correlation with and between the outcropping sequences of carbonates in the peripheral basins. Beneath this carbonate unit, the basal siliclastic sequence (Sequence 0) tends to thicken towards the centre of the CB (to up to ca. 1,100 m). Overlying the carbonate unit is a predominance of siliciclastic sequences with intercalation of thin carbonate layers, defined in the two deep exploration wells and in the seismic profiles as Sequences 2 and 3 (1,700 to 4,100 m), and here attributed to the late Neoproterozoic-early Paleozoic.

In the marginal West Congo, Lindian and Katangan basins, recent observations suggest that the uppermost clastic sequences (the Inkisi, Biano and Banalia Groups) are not affected by Pan-African deformations and therefore may be early- to mid-Paleozoic in age (Alvarez et al. 1995; Master et al. 2005; Batumike et al. 2006; Tack et al. 2008; Kampunzu and Cailteux 1999; Kampunzu et al. 2009; Cailteux et al. 2007; Tait et al. 2011).

In the CB, seismic Sequences 1 to 4 have been locally affected by a compressional tectonism event responsible for inversion structures such as folds and thrusts (Daly et al. 1992 and Kadima et al. 2011a). An erosional unconformity separates Sequence 4 from Sequence 5. We consider that the first four sequences form the late Neoproterozoic-early Paleozoic sedimentary record of the CB, with the lower major erosional surface represented by a Pan African unconformity.

Conclusion

A series of basins formed in Central Africa at the periphery of the Congo Shield and the large CB formed near its centre during the early Neoproterozoic by rifting and mafic magmatism related to the break-up of Rodinia. The early phase of the CB developed during this time along a NW-SE elongated structure corresponding to the Mbandaka-Dekese axis, intruded by mafic material that locally densified the crust; and was filled subsequently by up to 9 km of Neoproterozoic to Cenozoic sediments following long term (ca. 700 million years) thermal- and density-driven subsidence. Indirect observations suggest that the first seismic-stratigraphic sequence in the CB (Sequence 0) may consist of syn-rift clastics, with slightly divergent reflectors, followed by the deposition of carbonates, with an undetermined amount of evaporites (Sequence 1), and then two siliciclastic sequences with thin carbonate layers and tillites interbedded (Sequences 2 and 3). These four sequences are grouped in the seismic

Unit A of Kadima et al. (2011a), which is more than 2,360 m thick in the Mbandaka-1 well and up to 6,400 m thick along Line L51. They all have been affected by contractional deformation interpreted to be related to Pan-African orogenesis, causing basin inversion. They are therefore considered as of pre- to syntectonic relative to this event and are thus of Neoproterozoic age.

A regional unconformity truncates these structures and forms the base of Sequence 4 (1,400–1,900 m thick). This sequence comprises undated red sandstones at the base, followed by glacial to peri-glacial sediments of Late Carboniferous—Permian age. It is delineated at the top by a second regional tectonic unconformity and forms the seismic Unit B of Kadima et al. (2011a). This unit is less deformed than the four deeper sequences, and mainly by the reactivation of earlier structures in Unit A. The overlying Sequence 5 (Seismic Unit C of Kadima et al. 2011a) contains essentially continental formations attributed to the Upper Jurassic-Cenozoic and is between 800 m to 1,200 m thick.

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