The Congo Basin: Stratigraphy and subsurface structure defined by regional seismic reflection, refraction and well data

Damien Delvaux *(1), Francesca Maddaloni (2), Magdala Tesauro (2,3), Carla Braitenberg (2).

1 : Royal Museum for Central Africa, Dept. Earth Sciences, Tervuren, Belgium
2: University of Trieste, Department of Mathematics and Geoscience, Trieste, Italy
3: University of Utrecht, Department of Geosciences, the Netherlands
*Corresponding author, Email: damien.delvaux@africamuseum.be

Abstract

The Congo basin (CB) occupies a large part of the Congo craton, which derived from the amalgamation of different cratonic pieces. As intracratonic basin, it initiated as a failed rift in late Mesoproterozoic and evolved during the Neoproterozoic and Phanerozoic in an intraplate setting. For this reason, the CB can be considered a natural laboratory for investigating the processes that govern the long–term evolution of continental interiors. In this study, we reconstructed the stratigraphy and tectonic evolution of the CB using all available and geological seismic data (reflection and refraction seismics, borehole and field data). We interpreted almost 2600 km of seismic reflection profiles and well log data located inside the central area of the CB (the "Cuvette Centrale"). The obtained model will be further constrained by aeromagnetic and satellite gravity data and density measurements from rock samples in a next paper. Results show that the depth of the basement varies quite significantly, defining a series of structural highs and depocenters developed throughout the history of the basin. The major controlling factors for the development of the CB are, besides

the deep geodynamic processes, the inherited heterogeneity of the pre-Neoproterozoic basement, the tectonic evolution of Rodinia, Gondwana and Pangea amalgamation and breakup, and environmental conditions influenced by the drifting through the South Pole towards its present-day equatorial position and global climatic fluctuations between icehouse and greenhouse conditions.

Key Words: Congo Basin, Intracratonic basins, Basin Tectonic Evolution, Sediments.

1. Introduction

The Congo Basin (CB), also known as “Cuvette Centrale”, is a roughly circular basin located in the center of the African plate (Fig. 1). It extends for about 1.2 million km^2 from the Central African Republic (CAR) in the North to Angola in the South, occupying most of the Democratic Republic of Congo (DRC) and the Republic of Congo (RC). It is considered as a typical intracratonic basin, due to its slow and long-lived subsidence history and the largely unknown formation mechanisms (Veach, 1935; Crosby et al., 2010; Kadima et al., 2011a; Buiter et al., 2012). Hydrocarbon exploration in the CB, using geological and geophysical methods, started in the 1950’s and continued during the following decades (Evrard, 1957; Jones et al., 1960; Lawrence and Makazu, 1988, Daly et al., 1992), along with field campaigns in its peripheral parts (Raucq, 1957, 1970; Verbeek, 1970; Lepersonne, 1977; JNOC, 1984). Despite the possible geo-resources potential of this basin (Delvaux and Fernandez, 2015), the existing geophysical and geological data have not been fully exploited and important scientific questions concerning its structure and tectonic evolution remain. The CB has been repeatedly reactivated by global and local compressional and extensional tectonic events (Hartley and Allen, 1994; Kadima et al., 2015; Linol et al., 2015a). During the first part of its development, it also shared its intraplate history with other intracratonic basin in the Gondwana supercontinent. The CB is thus a natural laboratory to investigate the processes that govern the long–term evolution of continental interiors.

The history of the geological and geophysical investigations in the CB has been reviewed in Kadima et al. (2011a, 2015). In the 1950's, field works, gravity surveys, and several seismic refractions profiles were carried out. The first exploration campaigns were undertaken between 1952 and 1956 by REMINA (Société de Recherche Minière en Afrique), a.o. with the drilling of two fully cored stratigraphic wells (Fig. 2), in the localities of Samba (2.039 m deep; Cahen et al., 1959) and Dekese (1.856 m deep; Cahen et al., 1960) (Fig. 2). The resulting data and documentation of these campaigns (original data and notes, publications, geological samples, and the entire cores) were donated to the Royal Museum for Central Africa (RMCA) for further use in scientific studies.

A second exploration campaign was organised by a consortium of oil companies in the 1970's, acquiring ~2600 km of seismic reflection profiles, airborne aeromagnetic surveys covering most part of the basin in the DRC, and additional field sampling. Two deep (~4.3-4.6 km) exploration wells, taking mostly drilling cuttings (Mbandaka-1 and Gilson-1) were drilled in 1981 by Esso Zaire (Fig. 2).

In recent years, renewed interest was driven by the availability of a high resolution global gravity field dataset derived from the GOCE satellite that allowed for the first time to recover geological features across the entire African continent, also in areas with scarce field observations (Braitenberg, 2014). The satellite gravity data led to several new geodynamic models to explain the huge geoid anomaly centred on the CB and the long-term evolution of the basin (Downey and Gurnis, 2009; Crosby et al., 2010; Kadima et al., 2011b, Buiter et al., 2012). The available geological and geophysical data were used to revise and/or update the stratigraphy and tectonic evolution of the basin (Kadima et al., 2011a, 2015; Sachse et al., 2012; Linol et al., 2015a; 2015b; 2015c; Lucazeau et al., 2015; Caillaud et al., 2017; François et al., 2017). A new field campaign in the CB was initiated to evaluate its hydrocarbon potential (Delvaux and Fernandez, 2015).

1.1. Existing views on the CB evolution and formation

The CB has a long and complex history of sediment accumulation, tectonic reactivations and erosion, initiated in the Precambrian with different extensional phases interrupted by short-lived compressional phases (Lucazeau et al. 2015), similarly to other intracratonic basins (Lindsay et al., 2002; Burke and Gunnell, 2008). The CB overlies a thick rigid lithosphere (~200 km; Crosby et al., 2010) and requires a deep compensation level to explain the underlying long-wave negative gravity anomaly, one of the largest on Earth (Hartley and Allen, 1994; Downey et al., 2011; Buiter et al., 2012). This anomaly is considered as the result of the combined effects of the low density of its thick sedimentary units (~9 km) and the presence of a high-density body below the crust, which isostatically compensates the sediments (Hartley and Allen, 1994).

According to Kadima et al. (2011a) and Buiter et al. (2012), a large part of the older subsidence history of the CB is controlled by post-rift thermal subsidence. Further studies link the CB formation to tectonic uplift of swells surrounding the basin (Burke and Gunnell, 2008) or to lithospheric delamination (Downey et al., 2011). These studies have based their hypotheses on the stratigraphy reconstructed from the interpretation of the seismic reflection profiles, calibrated by the four deep wells (Samba, Dekese, Mbandaka, and Gilson; Fig. 2).

1.2. Study approach

Despite the already abundant literature on the subject, the spatio-temporal evolution of the CB within the global plate tectonic and climatic context is still poorly known. In a considerable effort, the available litho- and biostratigraphic data have been recently highlighted in several recent papers, but they have not yet been fully used at the scale of the basin. We construct here a three-dimensional geological and stratigraphic model of the CB for the main time periods, in order to investigate the architecture and evolution of the CB.

To achieve this, we reconstructed the structure of the basin using all the available seismic and geological data (seismic reflection, seismic refraction, borehole, and field data), taking advantage of the apparent lateral continuity of the stratigraphic units. We re-examined the calibrated seismic reflection profiles and interpreted the total of about 2600 km of seismic profiles, acquired along 35 lines in the CB, between 1974 and 1976, by an Esso-Texaco consortium. The obtained model will be validated by aeromagnetic, satellite gravity data, and density measurements from rock samples in a next paper (Maddaloni et al., 2020).

The interpreted two-way travel time (TWT) profiles were converted into depth profiles and used to compute a series of major sedimentary layers by kriging interpolation. The obtained results enable to identify the main sedimentary depocenters of the CB and reconstruct its tectonic and geological history in greater details than in previous studies. In particular, from the work of Daly et al. (1992) and Kadima et al. (2011a), we provide a new lithostratigraphic subdivision with newly defined Supergroup and Group. Furthermore, the analysis of the seismic reflection profiles led us to identify several small tectonic features reflecting the influence of far-field compressional tectonic events within the basin. The ~ 1.000 Ma evolution of the CB is then placed into a broad tectonic context of Rodinia, Gondwana and Pangea amalgamation and breakup, and glacial climatic fluctuation with several glacial events.

2. Tectonic setting and factors controlling the evolution of the Congo Basin

The CB started to form in early Neoproterozoic (Kadima et al., 2011b, 2015), or, as we will show in this study, possibly even earlier, in late Mesoproterozoic. It developed within the Precambrian basement of Central Africa (Fig. 1), originally defined as the Congo Craton by Cahen (1954). De Waele et al. (2008) and Fernandez-Alonso et al. (2015) expanded the definition of the Congo Craton to the assemblage of several central-African Archean nuclei plus the Sao-Francisco and Tanzania cratons; all welded together at the end of the Mesoproteroroic by Meso-and Paleoproterozoic belts. Others named this assemblage the Central African Shield (de Wit and Linol, 2015) or the great Congo Craton (Kadima et al., 2015). We prefer here to keep the Congo Craton term as understood by De Waele et al. (2008) and Fernandez-Alonso et al. (2015). The Congo Craton is surrounded from all sides by Neoproterozoic belts (Abdelsalaam et al., 2002; Frimmel et al., 2006; Gray et al., 2008; Collins and Pisarevsky, 2005; Fritz et al., 2013; Foster et al., 2015).

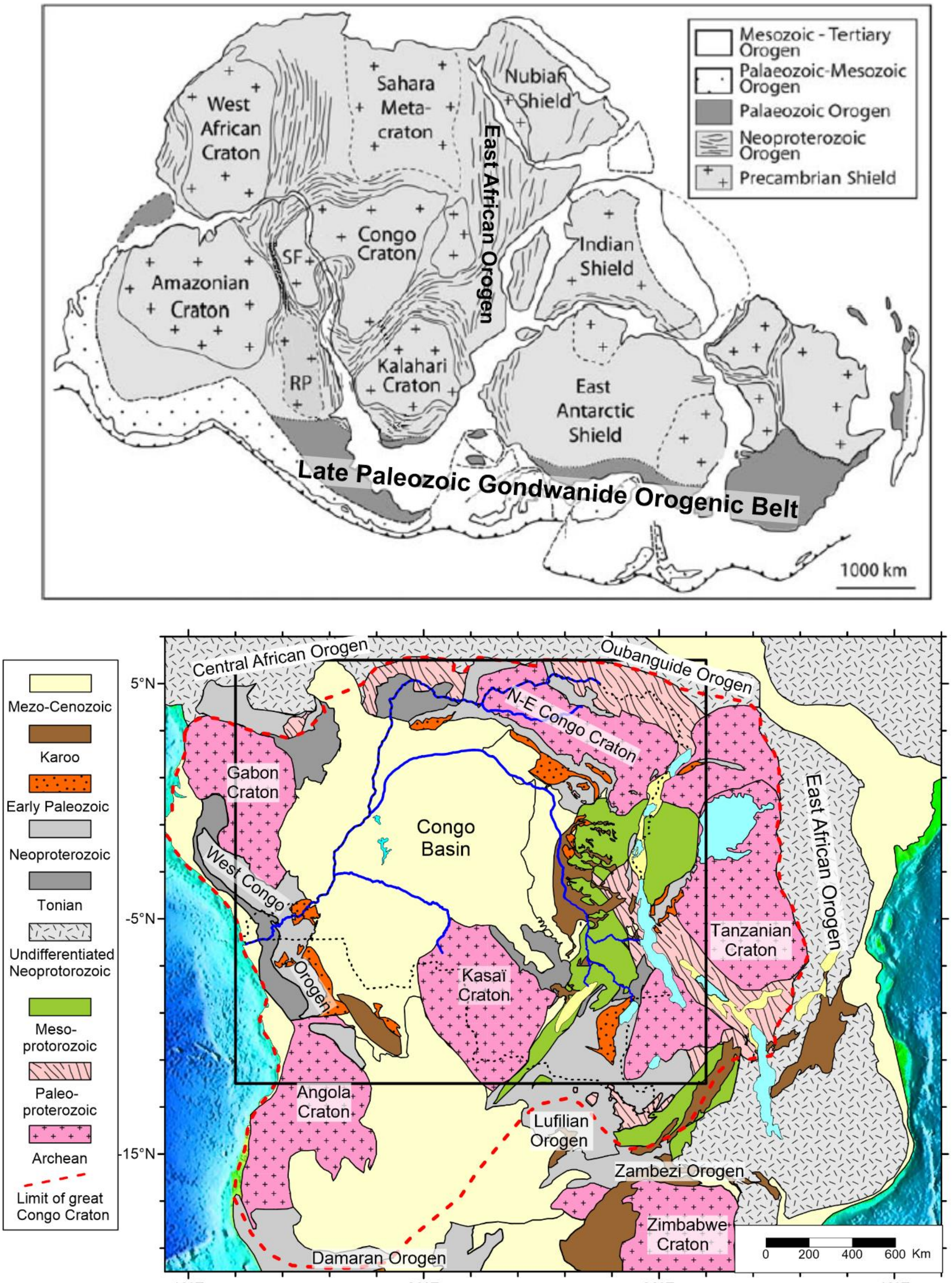


Fig. 1. Geological setting of the Congo Basin. **a**: Map of Gondwana (adapted from Gray et al., 2008), with position of the Gondwanide orogenic belt from Trauw & de Wit (1999). **b**. Congo Craton and surrounding Pan-African orogenic belts (adapted from Kadima et al., 2015). Black rectangle delimits the Congo Basin as detailed in Figure 2.

Since the late Mesoproterozoic, as the result of Rodinia amalgamation, the Congo Craton comprised the NE-Congo, Gabon, Angola, Kasaï, Tanzania, and São Francisco cratons, together with the Bangweulu block (Collins and Pisarevsky, 2005; Fernandez et al., 2015). During Gondwana amalgamation, it interacted between 650 and 540 Ma with the West African craton along the Central African Orogenic Belt (Toteu et al., 2004; Saha-Fouotsa, 2019). At about 630 Ma, it entered in continental collision with the Sahara Metacraton, generating the Oubanguide Orogen (Poidevin, 1985) and with Neoproterozoic India in the East, generating the East African Orogen (Fritz et al., 2013). At about 570 Ma, closure of the ocean embayement between the São Francisco Craton (eastern Brazil) and the Gabon-Angola cratonic nucléi generated the Araçuaí-West Congo Orogen (Pedrosa-Soares et al., 2008; Santiago et al., 2020). Convergence and collision between the southern margin of the Congo Craton and the Zimbabwe Craton (small northern part of the Kalahari Craton) generated the Damara Orogen in the west, peaking at about 565 Ma (Frimmel et al., 2011) and, in the east, the twin Lufilian Orogen, peaking at about 595 Ma (Cailteux and De Putter, 2019) and Zambezi Orogen, peaking at 560-550Ma (Kuribara et al., 2018). Late tectonic convergence between the Dharwar Craton (India) relative to the Congo Craton at ~530 Ma generated intraplate reactivations between the Congo-Bangweulu and the Tanzania cratons (Delvaux et al. 2012) and also within the Lufilian Orogen (Kipata et al, 2013; Cailteux and De Putter, 2019). All these tectonic events are likely to have caused late Neoproterozoic (Pan-African) intraplate deformations in the heterogeneous Congo Craton, which could have been recorded in the CB.

The CB developed over three NW elongated Archean nuclei (Gabon, Kasaï and NE-Congo) that form the central core of the Congo Craton, and surrounding the concealed central part of the Congo Craton (de Wit and Linol, 2015). The presence of cratonic lithosphere beneath the CB has recently been confirmed by seismic tomography by Celli et al. (2020), who identified at least three distinct high-velocity blocks. These blocks represent remnants of likely larger Archean nucléi, which were partly eroded by their interactions with thermo-chemical mantle plumes (e.g., Hu et al., 2018) or by other processes (e.g., Liao et al., 2017). Therefore, the original heterogeneous structures of the Archean cratons and their possible successive modifications during geological time are responsible for the primary basement anisotropy and the following development of the CB.

After the final junction between East and West Gondwana, at about 530 Ma, the CB became located in the center of the Gondwana supercontinent. A new paleo-pacific active margin formed along the southern edge of the continent during the Phanerozoic (Milani and de Wit, 2008). Once amalgamated, the entire Gondwana supercontinent drifted first southwards, then northwards, bringing the CB into a polar-centered, and back into an equatorial position. According to the apparent polar wander curve for Gondwana (Scotese et al., 1999; Torsvik and Cocks, 2011; 2013), the South pole was located in W Africa (Mali/Algeria) in early Cambrian, NW Africa (Morocco) in early Ordovician, SW Africa (Ivory Coast) in late Ordovician, western coast of Central Africa (Namibia) in early Devonian, Namibia in late Devonian (Frasnian), Central Africa in late Devonian (Famennian), north of the CB in early Carboniferous (Tournaisian-Visean), and central Antarctica (then adjacent to South Africa) in late Carboniferous. From that period, the general tendency for the Gondwana continent was to drift northwards, bringing the CB progressively into a more equatorial position. In parallel, the global climate fluctuated with several ice ages (Ice House), during which one or two poles were covered by permanent ice, followed by global warming and warm ages (Hot House), without permanent ice cover at the poles. Major Ice House periods occurred during the Cryogenian (coinciding with the assembly of Gondwana), late Ordovician - earliest Silurian (brief but extensive), and in late

Devonian–Carboniferous to early Permian (Frakes et al., 1992). The regional paleoclimatic conditions of the plate interior were controlled by the latitudinal movement of Gondwana, global climate evolution, and morphology of the plate interior.

During the lifespan of the Gondwana supercontinent, interactions with the adjacent plates generated plate-boundary forces that propagated into the continental interior as far-field stresses (Daly et al., 1991; de Wit and Ransome, 1992). Collision with Laurentia on its NW edge in the late Carboniferous – early Permian resulted in the Appalachian-Mauritanian-Variscan orogeny (Kröner and Römer, 2013). Subduction along the southern margin of Gondwana resulted in the Gondwanides orogeny (Fig. 1a) with the Sierra de la Ventana-Cape Fold Belt in the late Permian – early Triassic (Trouw and de Wit, 1999; Milani and de Wit, 2008) and earlier collisions (Ordovician-Devonian) in the NW, along the South American domain (Milani and de Wit, 2008). Gondwana breakup which started around 200 Ma ago (early Jurassic), also influenced the tectonic evolution of the CB, with the giant Okavango mafic dyke swarm across NE Botswana emplaced at 178-179 Ma (Le Gall et al., 2005), the late Jurassic opening of the Indian Ocean (Sinha et al., 2019), the early Cretaceous opening of the South Atlantic Ocean (Heine et al., 2013), and the Neogene East African rifting (Macgregor, 2015).

According to Kadima et al. (2011a, 2011b), the CB started as a failed rift system. The fossil rift would be represented by the WNW-trending Kiri basement high that separates the basin in two parts and coincides with pronounced axial magnetic and gravity anomalies. Following Daly et al. (1992), the Kiri High formed by crustal contraction and uplift in the late Paleozoic times, reactivating (inverting) the former rift structure. Kadima et al. (2011a), instead, using combined gravity and magnetic modeling, proposed that the poorly defined seismic zone with transparent seismic facies which mark the 'basement' of the Kiri High (see Figure 7 below) can be adequately modelled by intermediate salt (evaporate) and sediment density, instead of an uplifted crystalline basement. They therefore propose a gradual lateral change in density from the adjacent basins towards the Kiri High. They also suggested that observed tectonic structures of the CB are the typical product of the inversion processes during the two major tectonic events (Pan-African and Permo-Triassic) and induced by movement of salt present in the Neoproterozoic sediments.

3. Data obtained from exploration campaigns

A first exploration campaign in the Congo Basin was conducted in 1952-1956 by the 'Syndicat pour l'étude géologique et minière de la Cuvette congolaise', with field work, refraction seismics and two c. 2000m deep stratigraphic wells, fully cored (Samba and Dekese) drilled by the REMINA. The resulting data (outcrop samples, drill cores), reports and publications are stored in RMCA collections and available for research. Furthermore, between 1970 and 1984, Shell, Texaco, and JNOC oil companies acquired new data with aeromagnetic surveys. They also acquired more additional gravity data, geochemical sampling, and about 2600 km of seismic reflection profiles, in the CB over an area of 500.000 km^2 between the Congo and Kasaï rivers. The seismic profiles were recorded both along watercourses (lines R) and roads (lines L) (Fig. 2). In 1981, the exploration wells Mbandaka-1 (4350 m; Esso Zaire S.A.R.L., 1981a) and Gilson-1 (4563 m; Esso Zaire S.A.R.L., 1981b) were drilled by the Esso Oil Company (Fig. 2). The cuttings of the cores were sampled every 10 m, but they are no longer accessible. The Mbandaka-1 well terminated in massive salt deposits of Proterozoic age with anhydrite inter-beds, after encountering stromatolitic carbonates, while the Gilson-1 well terminated in massive dolomite. None of the four wells reached the crystalline basement. Only the Jurassic to Recent sediments encountered in the Dekese and Samba wells were accurately dated paleontologically but the stratigraphic position of the deeper deposits is more problematic. Analysis of the data lead to a preliminary subdivision of the basin stratigraphy in three major sedimentary sequences (Proterozoic, Paleozoic-Triassic and Jurassic-Cretaceous) separated by major tectonic unconformities (Pan-African and Basal Jurassic) and allowed to define its global architecture and tectonic evolution (ECL, 1988; Lawrence and Makazu, 1988; Daly et al, 1992; Kadima et al., 2011a).

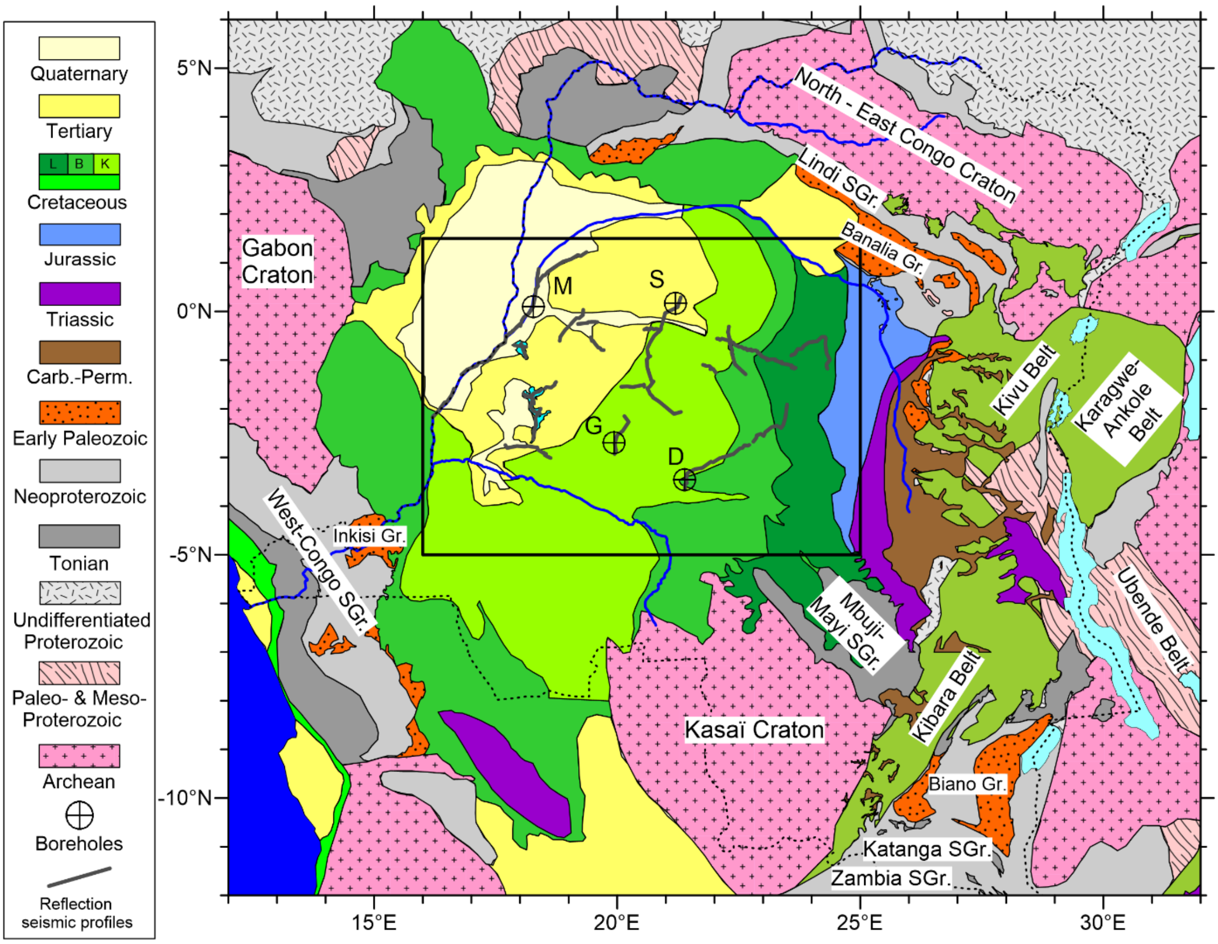


Fig. 2. Surface geology of the Congo Basin (adapted from Kadima et al., 2015). Black circles: deep wells: D (Dekese), G (Gilson-1), M (Mbandaka-1), S (Samba). Broken black lines identify reflection seismic lines. Black rectangle delimits location of the study area.

4. Revised seismic stratigraphy of the Congo basin

The bowl-shaped CB (hence its name “Cuvette Centrale”) shows progressively older outcropping geological series towards its periphery (Fig. 2). Integrating this with the well data and thanks to the remarkable lateral continuity of the stratigraphic units, Daly et al (1992) proposed a first general stratigraphic column of the CB. It was revised by Kadima et al. (2011a, 2015) and Linol et al. (2015b, 2015c) based on the re-analysis of some key seismic profiles and well data. The lithostratigraphic units are named according to the last version of the Geological map of the RDC at 1/2.500.000 (Fernandez-Alonso et al., 2017) as detailed in his Explanatory Notice (Fernandez-Alonso et al., 2017), published by the Ministry of Mines of the DRC. A series of stratigraphic names have been changed according to the Stratigraphic Guide of the International Commission on Stratigraphy (ICS). In particular, the formations described in the literature as Haute-Lueki and Stanleyville Groups are now respectively named as Lueki and Kisangani Groups.

4.1 Lithostratigraphy and age control from well and outcrop data

The lithostratigraphy of the CB is known from a few deep and shallow wells and from surface outcrops. The good lateral continuity of the sedimentary layers and seismic reflection profiles allows extending the stratigraphic framework over the entire basin. Almost all stratigraphic sequences, from the late Mesoproterozoic to the Cenozoic, are illustrated by well and/or outcrop data (Fig. 3). The Proterozoic to Cambrian sequences are exposed along the margins of the CB (Delpomdor and Préat, 2015). The pre-Jurassic sequences of the deep Gilson and Mbandaka wells are almost unconstrained by biostratigraphy and, therefore, their interpretation is difficult and varies from one study to the other. For these sequences, we preferred to follow the interpretation of Kadima et al. (2011a; 2015), which is based on unpublished exploration reports, instead of the one presented in Linol et al. (2015b).

The oldest sequences of the CB are illustrated by the Mesoproterozoic Mbuji-Maji Supergroup, which is found in two NW-trending depressions between the Kasaï Craton and the Kibara belt of Katanga (Fig. 2). They comprise a lower BI Group of mostly clastic sediments, dolomitized on top, and an upper BII Group of dolomitic limestones, surmounted by dolerite lava (Raucq, 1957, 1970; François et al., 2017; Balukiday et al., 2018).

The Neoproterozoic sequences are typified by the Lindi Supergroup, which outcrops in the northern part of the CB (Fig. 2) and was intensively studied by Verbeek (1970). Their correlation with the well and seismic data in the CB was proposed by Daly et al. (1992).

The lower Paleozoic sequences are represented by thick cross-bedded red arkosic sandstones outcropping along the margin of the CB (Fernandez-Alonso et al., 2017) as the Inkisi Group (Alvarez et al., 1995; Affaton et al., 2015), Banalia Group (Verbeek, 1970) and Biano Group (Cailteux and de Putter, 2019) and which are found also in the Samba and Dekese wells (Cahen et al., 1959, 1960).

The overlying Karoo series comprise from top to bottom, red-sandstones of the Lueki (ex-Haute-Lueki) Group (Triassic), coal-bearing mudstones and psammitic sandstones of the Upper Lukuga Group (Late Carboniferous to Upper Permian), and glacial to periglacial tillite and varval black shales of the Lower Lukuga Group (Upper Permian). Their age is relatively well constrained by spores and pollens (Boulouard and Calendra, 1963; Boze and Kar, 1976, 1978; Cahen and Lepersonne, 1978). The Lower Lukuga Group is well known in the Dekese well cores (Cahen et al., 1960), with a thickness of up to 1000 m of glacial-lacustrine tillites and periglacial varval black shales (not present in the Samba Well). The entire Karoo series is exposed along the Lukuga River valley and in the Lukuga Coal field (Fourmarier, 1914; Jamotte, 1931), in the Luama graben along the Tanganyika rift valley. The Upper Lukuga

Group and its transition to the Lueki Group is well evidenced in a coal exploration drill well (Cahen and Lepersonne, 1971). The Lueki Group is present in small thickness in the Dekese Well, but not in the Samba Well (Lombard, 1961) and known as part of the Casanje Group in Angola (Cahen, 1981). The Lukuga and Lueki sediments are also present in the Gilson and Mbandaka wells, but the dominant clastic facies of these wells does not allow to precise their biostratigraphic correlations.

The Jurassic to Cretaceous series are the best studied ones in terms of biostratigraphy, sequence stratigraphy and lithostratigraphy. They were dated by ostracods (Grekoff, 1957; 1960), phyllopods (Defretin Lefranc, 1967), pelecypods (Cox, 1960); spores/pollen (Boulouard and Calendra, 1963; Masheshwari et al., 1977) and fishes (de Saint-Seine, 1955; de Saint-Seine and Casier, 1962; Casier, 1965; Taverne, 1975a, 1975b). Their biostratigraphy has been revised by Colin (1994) and presented in detail in Linol et al. (2015b, c). Their sequence stratigraphy and depositional environment were studied by Linol (2015c) and Roberts (2015). These series start by the late Jurassic (Kimmeridgian) Kisangani (ex-Stanleyville) Group, well developed along the Lualaba River (i.e. the Congo River upstream Kisangani) where it forms a large basin (Passau, 1923). In this region the series starts by organic-rich lacustrine calcareous siltstones and shales (Type I kerogen; Sachse et al., 2012) and grades upward to more oxidized sandstones and siltstones in a dryer environment (Caillaud et al., 2017). They overly limestones with stromatolites of probable Neoproterozoic age, themselves resting over basement quartzites and gneisses.

Jurassic sediments are present in the Samba well (Cahen et al., 1959) consisting of a lacustrine sequence at the base, locally organic-rich, surmounted by red siltstones and sandstones with geochemical evidence for hot and arid conditions (Myers et al., 2011). They have also been recognized in small thicknesses the Gilson and Samba Wells (Esso-Zaïre SARL, 1981a, 1981b; Linol et al., 2015b), in boreholes in Kinshasa and Brazzaville, lying directly over the Inkisi red sandstones (Egoroff and Lombard, 1962; Defrétin-Lefranc, S., 1967), and in the cover series of the Kasaï Craton in the Tshikapa area (Roberts et al., 2015).

Arid conditions then developed, with deposition of eolian cross-bedded sandstones, recently identified in Dekese and Gilson wells, which define the new Dekese Group (Linol et al., 2015c). Its age is indirectly constrained as early Cretaceous from the surrounding sediments. More humid conditions followed in Albian – Cenomanian as evidenced by the deposition of sandstones and mudstones of the Loia and Bokungu Groups (Colin, 1994). Deposition started in a lacustrine environment, locally anoxic with black shales (mixture of kerogens of Type I and II; Sachse et al., 2012), then evolved into a shallower, fluvial environment with carbonated mudstones.

The Kwango Group is known mainly in the southern and western parts of the basin (Cahen and Lepersonne, 1954; Linol et al., 2015c) and as cover of the Kasaï Craton (Roberts et al., 2015). It may have had a marine influence and its lower part is dated mainly by fishes, suggesting a Cenomanian-Turonian age (Casier, 1965; Taverne, 1976a, b) or Campanian-Maastrichtian (Gobbo-Rodrigues et al, 2003).

The cover sequences are regrouped in the Kalahari Group (Linol et al., 2015e; Fernandez-Alonso et al., 2015), with silcretes, calcretes and ferricretes covered by aeolian sandstones. They represent the weathering and denudation ‘African Surface’ of King (1963) and were formed under a regionally humid and hot climate of Central Africa. They are described as ‘Polymorph sandstones’ (grès polymorphes) by Lepersonne (1945). Thermal evolution modeling constrained by vitrinite data shows that during the late Cretaceous-Paleogene evolution of the landscape (Guillocheau et al., 2015), an estimate of 1000m (Sachse et al., 2012) or more (Lucazeau et al., 2015) of sediments were removed.

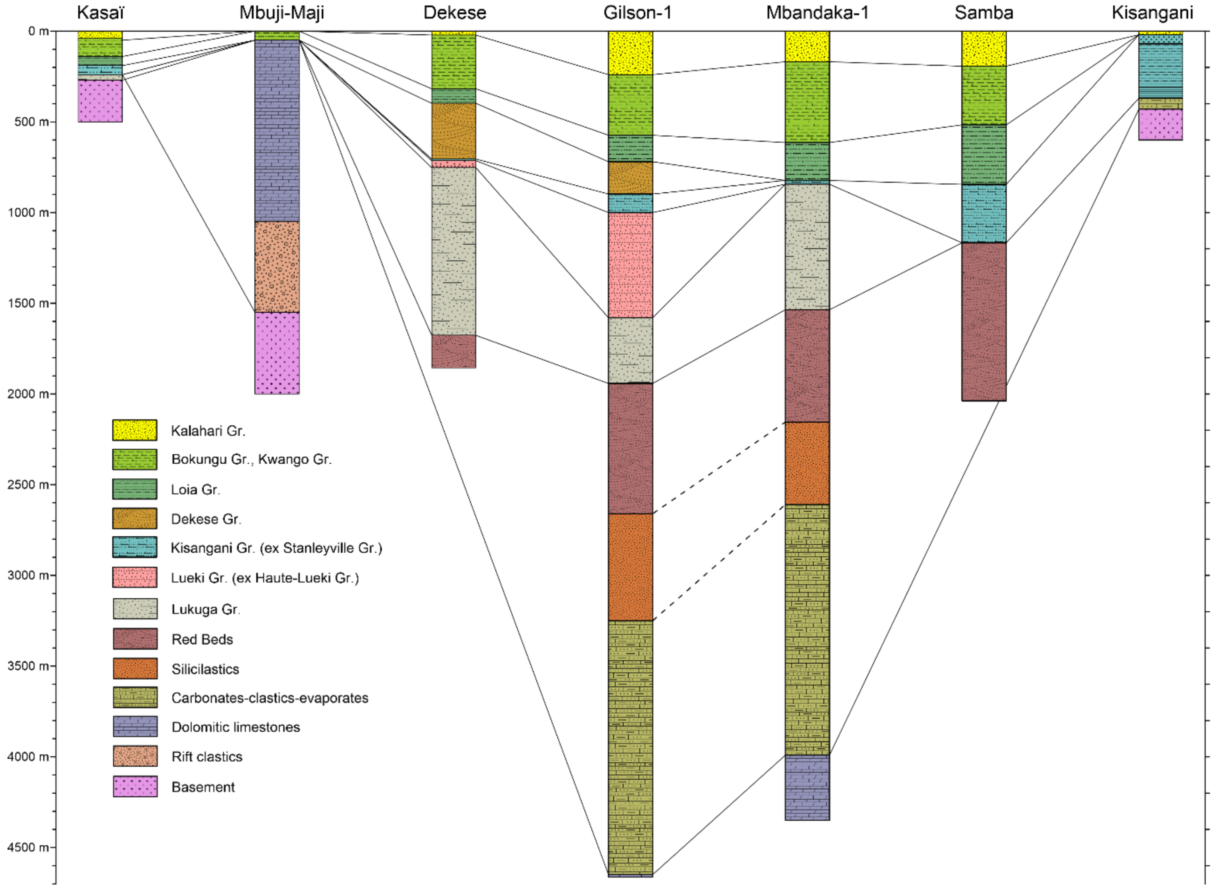


Figure 3 : Regional lithostratigraphic correlations of the wells across the CB. Data in tables in the Supplementary Materials.

4.2 New seismo-stratigraphic model

Starting from the existing seismo-stratigraphic models of Kadima et al., (2011a; 2015), we reinterpreted the entire seismic stratigraphy of the CB, using a new comprehensive analysis of the seismic profiles, integrated with the most recent works on the CB. This new stratigraphy of the CB with the description of the seismic sequences is displayed in Figure 4.

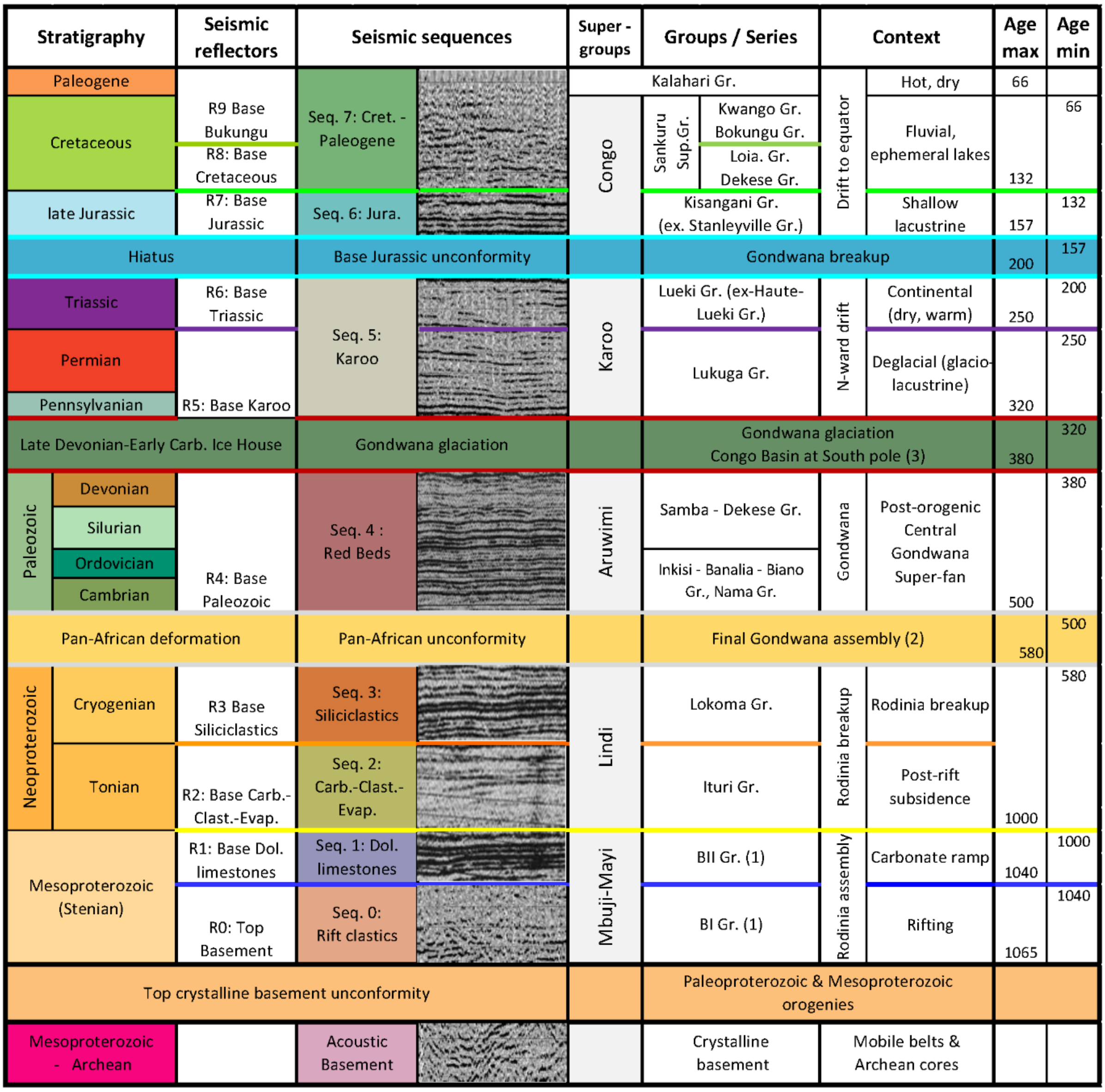


Figure 4. Composite seismo-stratigraphic model integrating well and outcrop data and seismic reflection profiles (Cahen et al., 1959; Esso-Zaire SARL, 1981a, 1981b; Sachse et al., 2012; Linol 2013; Delvaux and Fernandez-Alonso, 2015; Fernandez-Alonso et al., 2012; 2015 ; Kadima et al., 2015; Roberts et al., 2015; François et al., 2017; Caillaud et al., 2017). Age estimations from: François et al., 2017[(1)]; Fritz et al., 2011[(2)] andTorsvik and Cocks, 2011, 2013[(3)]. The thick coloured lines refer to the interpreted seismic reflectors in the profiles (Figs. 7-12).

The Mesozoic and late Paleozoic strata are directly constrained by the Samba and Dekese cored wells (Cahen et al., 1959, 1960), but the early Paleozoic and Proterozoic rocks remain poorly dated, as they do not contain datable material, except for the basal series. Their stratigraphic age is indirectly constrained by analogy with the Supergroups outcropping along the margins of the basin, and with the help of the two Gilson-1 and Mbandaka-1 wells (Esso-Zaïre SARL, 1981a, b) and the first interpretation of the Esso-Texaco reflection seismic profiles. The “infracambrian” stratigraphy was first correlated with the West Congo and the Katanga Supergroups, respectively to the west and south-east of the CB (Lawrence and Makazu, 1988). Daly et al. (1992) correlated it with the Lindi Supergroup (Verbeek, 1970) on the northern side of the CB.

The seismo-stratigraphy of the CB was later revised by Delpomdor et al. (2013b) and Kadima et al. (2015) with additional references to the Mbuji-Mayi Supergroup defined by (Raucq, 1957, 1970). This Supergroup outcrops against the Kasaï craton along the SE edge of the CB in the Sankuru-Mbuji-Mayi-Lomami-Lovoy (SMLL) sedimentary basin, which is considered to be a lateral equivalent of the basal units of the CB. The Mbuji-Mayi Supergroup has been deposited in a intracratonic failed-rift basin with a lower clastic sequence (BI) and an upper carbonate sequence (BII) indicative of a restricted marine carbonate ramp environment (Delpomdor et al., 2013a). It is covered and intruded by dolerite lavas, which mark the end of the deposition for the Supergroup, thus constraining its minimum age. Cahen et al. (1984) obtained a K-Ar age of 940 ± 20 Ma for these dolerites. In contrast, Delpomdor et al. (2013b) dated the depositional interval of the Mbuji-Mayi Supergroup between 1174 ± 22 Ma and ca. 800 Ma using δ13C of carbonates and obtained an Ar/Ar age of 882.2 ± 8.8 Ma for the dolerites. However, recent U-Th-Pb (François et al., 2017) dating shows that the diagenesis of the BI subgroup is between 1065 Ma and 1030 Ma. Similarly, conventional 207Pb/206Pb ages of 1040 Ma and 1065 Ma for galena samples in the upper part of the BI group were obtained by Cahen (1954), attributed to syngenetic growth of galena during diagenesis. Therefore, we consider that the Mbuji-Mayi Supergroup has a terminal Mesoproterozoic age and correlates with / represents the basal series of the CB. Despite its age, this sedimentary sequence remained in a low-grade thermal maturity, mostly restricted to the diagenesis domain (Balukiday et al., 2018).

We subdivided the seismic stratigraphy of the CB in a similar approach as Kadima et al. (2015), but consider 8 sequences (instead of 6), overlying the crystalline/metamorphic basement. Separated by the prominent Pan-African and Basal Jurassic regional unconformities identified by Lawrence and Makazu (1988), a first-order subdivision in three age groups can be made: (1) Meso-Neoproterozoic (sequences 0-3), (2) Paleozoic-Triassic (sequences 4-5) and (3) Jurassic-Paleogene (sequences 6-7) (Fig. 4).

4.2.1 Proterozoic (sequences 0-3)

The Proterozoic sedimentary sequences formed in a succession of rift and post-rift events, during the final stages of the Rodinia supercontinent amalgamation in (De Waele et al. 2008).

The Mesoproterozoic corresponds to the syn-rift sequences:

- Sequence 0 (rift clastics): low-amplitude, discontinuous, and transparent seismic patterns, which represent coarse siliciclastics, by analogy with the lower BI Group of the Mbuji-Mayi Supergroup;
- Sequence 1 (dolomitic limestones): highly continuous and parallel reflectors, considered an equivalent to the BII Group of the Mbuji-Mayi Supergroup. The top of this sequence was reached in the Gilson well at 4503 m deep and in the Mbandaka well at 3960 m. The latter stopped in interstratified massive salt, at 4350 m deep.

The Neoproterozoic is marked by continuous subsidence with carbonates and siliciclastics. It has been correlated (Lawrence and Makazu, 1988; Daly et al., 1992) with the Ituri (mostly carbonates) and Lokoma (siliciclastics and carbonates) groups of the Lindi Supergroup, separated by the Akwokwo tillite (Verbeek,1970):

- Sequence 2 (carbonates-evaporates-clastics): transparent seismic pattern with some medium to strong continuous reflectors, which could represent dominant carbonates and clastics (eq. Ituri Gr.), locally with some evaporates.
- Sequence 3 (siliciclastics): banded seismic pattern of moderately continuous reflectors representing dominantly siliciclastic sediments (eq. Lokoma Gr.).

As reported in Kadima et al. (2011b), Sr-isotope stratigraphy of the Akwokwo tillite allowed researchers to postulate that it corresponds to a Sturtian event (720 ± 30 Ma), and therefore, the Ituri group would be of Tonian age (1000-720 Ma), and the Lokoma group of Cryogenian age (720-635 Ma).

Sequences 1 to 3 are locally folded, faulted, and truncated by the Pan-African unconformity. The related tectonic deformation and subsequent denudation are explained as the result of intraplate deformation in response to the amalgamation of the continental blocks against the Congo Craton (Collins and Pisarevsky, 2005; Kadima et al., 2011a), as described above.

4.2.2 Paleozoic-Triassic (sequences 4-5)

Below the Basal Jurassic unconformity, the whole Paleozoic and Triassic was considered as a single sequence by Kadima et al. (2015). Here, it is further subdivided in two sequences, corresponding respectively to a newly defined Aruwimi Supergroup (see below) and the Karoo Supergroup, separated by the late Devonian – early Carboniferous Ice House event, during which the CB was close to the South Pole,:

- Sequence 4 (Red Beds): moderate to continuous parallel reflectors, wavier on top. The basal part of this sequence has been considered as equivalent to post-Pan-African early Paleozoic red arkoses ("red beds") outcropping at the periphery of the CB: the Inkisi Group in the Bas-Congo (now Kongo Central) region in the DRC, but also in the Republic of Congo and northern Angola (Alvarez et al., 1995; Straathof, 2011; Affaton et al., 2015), the Banalia Group in the Lindi region (Tait et al., 2011), the Biano Group in Katanga (Cailteux and De Putter, 2019), and the Upper Nama Group in Namibia (Blanco et al., 2011). The upper part of this sequence was reached in the Samba well from 1167 m to 2038 m and in the Dekese well from 1677 m to 1856 m, down to the bottom of the wells. The drill cores did not provided biostratigraphic material for dating. Detrital zircons in the Inkisi Group gave a maximum age of 581 ± 18 Ma (Straathof, 2011). The age of this sequence could be up to the late Devonian, just before the late Paleozoic Icehouse and late Devonian - early Permian "Karoo" glaciation over Gondwana.
- Sequence 5 (Karoo): discontinuous to moderately continuous parallel reflectors, more transparent than sequence 4. It was drilled in the Dekese well between 714 and 1677 m. The cores reveal alternating sequences of glacial diamictites (initially described as tillites) and varval clays of late Carboniferous to early Triassic (Karoo) age (Cahen et al., 1960), deposited in a large glacial lake (Linol et al., 2015). They correspond to glacial - deglacial sequences under glacial to cool climate (Lukuga Group), and end in a postglacial environment (Lueki Group), while the South Pole was migrating towards central Antarctica (Wopfner, 1999).

Between sequences 4 and 5, the Dekese well shows a stratigraphic break at 1677 m depth. The cored transition from sequence 4 to 5 shows a typical dark-brown diamictite with poorly sorted irregular rock fragments up to 14 cm large overlying, in an irregular contact, massive red-brown micaceous feldspathic sandstone with soft clay pebbles, locally weakly calcareous and cross-bedded downwards. This evidences an episode of erosion (and therefore a hiatus) before the beginning of the deglacial Karoo sequence.

The Karoo and Red Beds sequences are locally folded and truncated by the Basal Jurassic unconformity, which is marked by a stratigraphic hiatus, localized tectonic deformation and erosion related to far-field stresses caused by the Gondwanide Orogen (Trouw and de Wit, 1999). This intracratonic deformation caused tectonic activations in the CB (Daly et al., 1991) and in the Cape Fold Belt of South Africa (de Wit and Ransome, 1992).

4.2.3 Jurassic-Paleogene (sequences 6-7)

The Jurassic-Paleogene sequences appear as a continuous blanket over the entire basin. They overlie the Basal Jurassic unconformity (Lawrence and Makazu, 1988; Kadima, 2011a) that truncates all the Paleozoic to Triassic sequences and correspond to the sequence 5 of Kadima et al (2015):

- Sequences 6 (Jurassic) and 7 (Cretaceous): parallel highly continuous reflectors grading upward to wavier reflectors. They correspond to the late Jurassic Kisangani and Cretaceous Dekese (sensu Linol et al., 2016), Loia, Bokungu and Kwango Groups, assembled into the Congo Supergroup, and a thin Paleogene cover (Kalahari Group) (Linol et al., 2016). They were deposited in tropical to equatorial conditions, in shallow ephemeral-lakes, fluvial-deltaic and aeolian environments (Cahen 1954;

Lepersonne 1974; Cahen 1983a, 1983b, Colin, 1994; Linol et al., 2015c; Roberts et al., 2015; Caillaud et al. 2017). This sequence is the best known of the CB, as it has been reported in the four deep wells drilled in the CB and in outcrops and contains fossils that allow biostratigraphic determinations (for the late Jurassic-Cretaceous).

In the explanatory notice of the new geological map of the DRC at 1/2.500.000 (Fernandez-Alonso et al., 2015), the Jurassic Stanleyville formation has been redefined as Kisangani Group, and the continental Cretaceous series of the CB (Loia, Bokungu, Kwango of Lepersonne, 1974) grouped into the Sankuru Supergroup. Linol et al. (2016) proposed to regroup them altogether in a Congo Supergroup, which is consistent with the seismic stratigraphy, since they all appear as a single macro sequence, without seismic discontinuities.

5. Refraction seismics

Three field geophysical campaigns were conducted by the REMINA in the CB between 1952 and 1956 (Evrard, 1957). Among others, a refraction seismic survey was carried out with 117 points regularly positioned over the entire CB. The depth of refractors was obtained for these points, and isobaths were traced on a map (Evrard, 1960).

The sedimentary sequences characterized by velocities less than 3600 m/s were considered by Evrard (1957; 1960) as “cover series” (Jurassic to Paleogene, our sequences 5 and 6) on the base of the correlations with outcropping series and the Samba and Dekese cored wells. The 4200 m/s reflector was correlated with the top of the red arkoses (Red Beds) in the northern part of the basin and the top of the Triassic Lueki and Permian Lukuga groups (Karoo) in the southern part (our sequence 5). The Red Beds define our seismic sequence 4, which was considered at that time as the top of the Neoproterozoic “substratum” (Veach, 1935; Cahen, 1954; Lepersonne, 1977). Evrard (1957) also recognized the ambiguity of the nature of the substratum deduced from the sole measured velocities. An important outcome of that survey was to recognize that the basin is likely much deeper than originally thought.

Here, we digitized the isobaths of the 4200 m/s and 5200 m/s refractors and interpolated them using a standard kriging method (SURFER, Golden Software package) with a grid spacing of 0.1 degree. The interpolated maps (Fig. 5a, b), show the internal structure of the basin, with a WNW-ESE structural high separating the CB into two parts (the Kiri High), coinciding with the axial magnetic zone (Kadima et al., 2011a; Maddaloni et al., 2020). Two main depocenters were identified, that motivated the drilling of the Samba and Dekese wells (Fig. 5a, b). The southern limit of the deep part of the basin remarkably corresponds to the limit of the Kasaï craton under the sediment cover, as defined using the aeromagnetic data (Maddaloni et al., 2020).

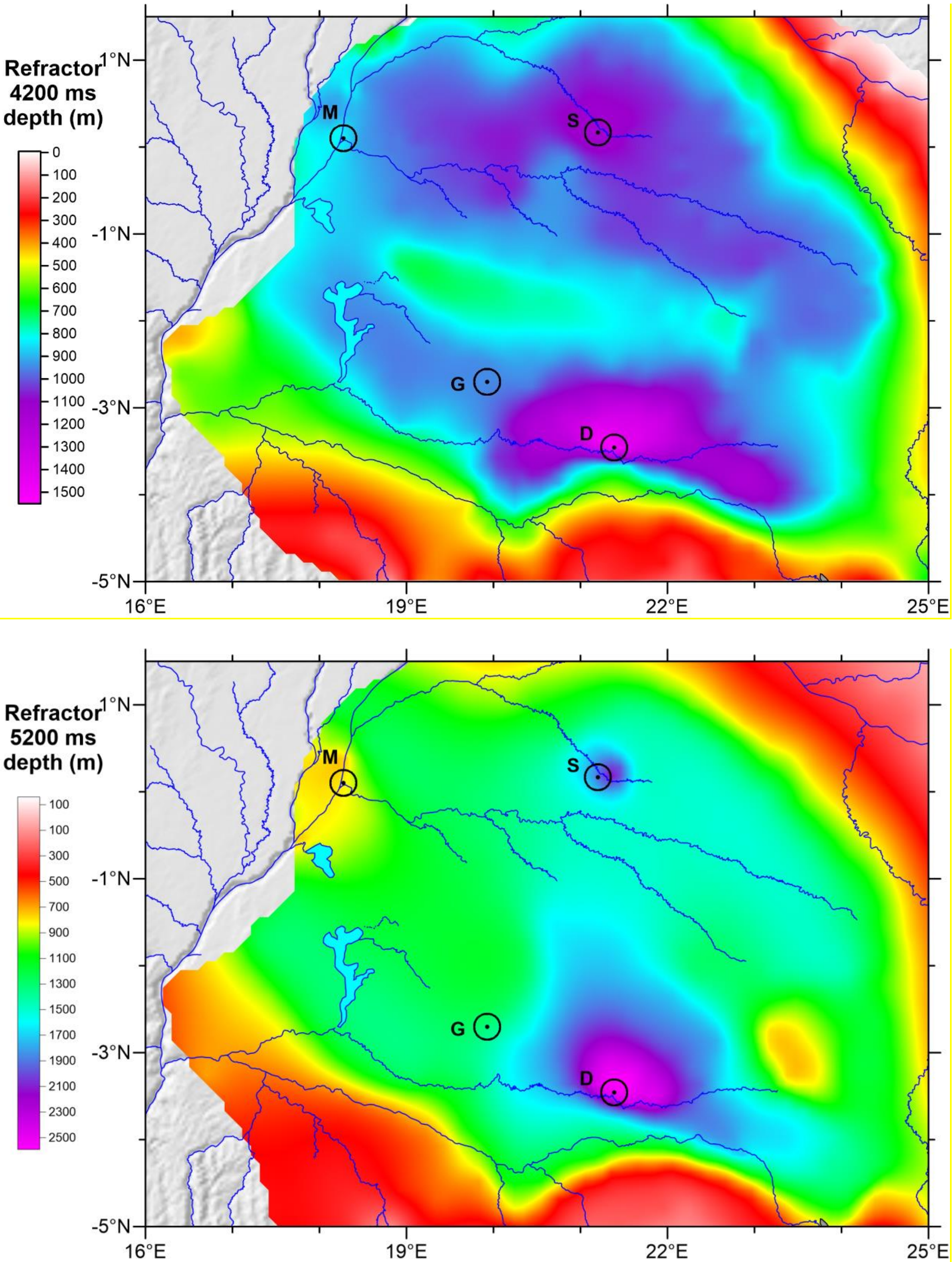


Figure 5. Refraction seismics (kriging interpolation of the data from Evrard 1960). Depth of the **(a)** 4200 ms and **(b)** 5200 ms refractor. Black circles show the location of the four wells drilled in the study area: D=Dekese; G=Gilson-1; M=Mbandaka-1; S=Samba.

6. Reflection seismics

As part of a second field exploration campaign, an extensive coverage of the central part of the CB by reflection seismic profiles has been performed by the Compagnie General de Géophysique in 1974. They were recorded with sources at 100 m interval consisting of groups of 3 vibrators 12.5 m apart, and geophones in series spaced by 5 m. The records were processed by the Geophysical Development Corporation (Houston, Texas) in 1986. Unfortunately, the original (digital) records are lost. The reflection profiles from scanned paper copies and their location map come from Kadima (2011).

There are 35 profiles for 2623 km in total (Fig. 6), 21 deployed along rivers and lakes (R profiles) and 14 along roads (L profiles). They were shot mainly at a high angle to the Kiri High, in order to better image the structure of the basin, with also some transversal lines. They cover in a rather homogeneous way the central part of the basin, from 1°N to 3.5°S and from 16.5°E to 24°E. In this work, the profiles were registered and analyzed using the Golden Software SURFER program. The geographic coordinates (WGS84 projection) of the seismic lines were digitized and the line lengths calibrated accordingly. In a reverse operation, the digitized points of the profile interpretations were re-located as geographic coordinates. The Common Depth Point boxes (CDP) giving the relation between TWT, seismic velocity and depth were used to compute depth-time curves for each profile by a third degree polynomial interpolation, needed for converting TWT to depth. For each profile, we used the most central CDP boxes as average for the entire profile.

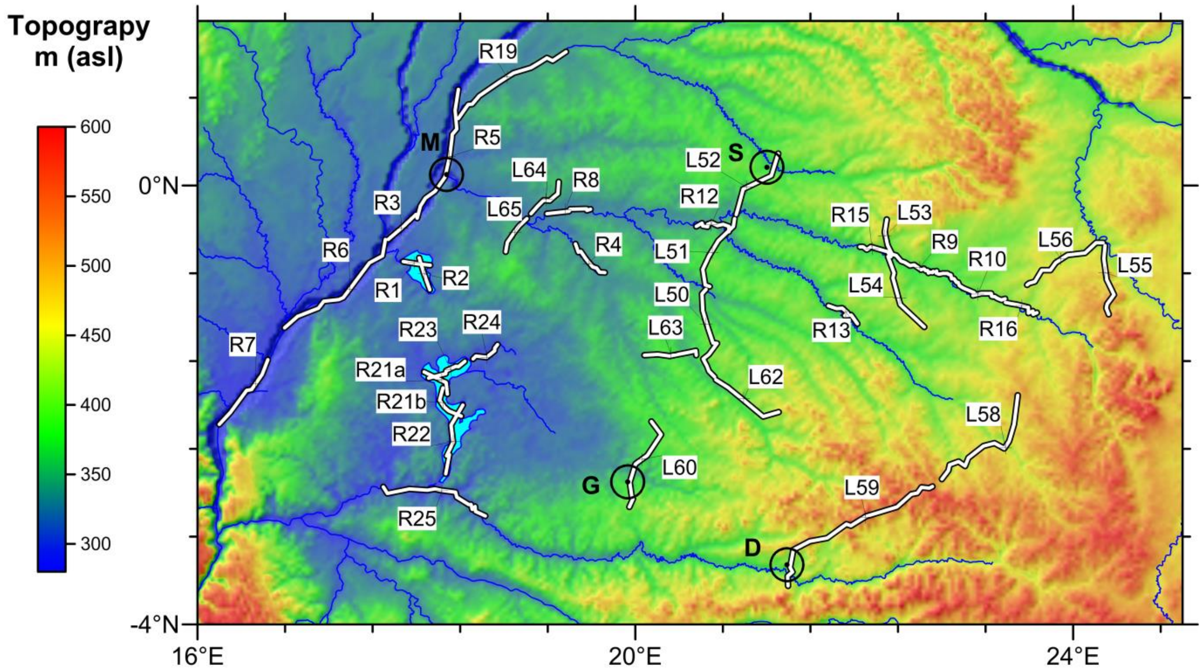


Figure 6. Topography map of the CB using (ETOPO 1, Amante et al., 2009). Black labels show the names of the seismic reflection profiles (white broken line). The hydrological system is displayed in blue. Black circles show the location of the four wells drilled in the study area: D=Dekese; G=Gilson-1; M=Mbandaka-1; S=Samba.

A preliminary interpretation of the seismic reflection profiles, calibrated with the Mbandaka-1 well, identified three major seismic units separated by major unconformities (Kadima et al., 2011a). Based on the interpretation of all available seismic reflection profiles inside the CB, we can identify now ten seismic reflectors (R0 – R9), of which seven can be recognized over the entire basin and two correspond to major tectonic unconformities. They define the eight (S0 - S7) seismic sequences overlying the acoustic basement (Fig. 4).

Some profiles were shot in series and thus have been assembled into combined profiles, generally calibrated by one or two wells. Some profiles intersect each other. From NW to SE, we distinguish:

- the SSW-NNE combined profile (R7-6-3-5-19), along the Congo River and calibrated by the Mbandaka 4350 m deep well;
- a group of profiles recorded along roads and rivers, near Ingende (L64-65, R4, R8);
- the series of profiles along Lake Tumba (R1, R2) and Lake Mai-Ndombe (R22, R24), together with profile R25 along the Lukenie river;
- the N-S Gilson-Samba combined land profile (L60-50-51-52), calibrated by the Gilson (4563 m deep) and Samba (2039 m deep) wells and intersected by three E-W oriented profiles (R12, L63, L62);
- a series of river and land profiles in the NE part of the basin, along the Tshuapa River between Bokungu and Ikela (R15-9-10-16) and across it (L53-54), along the Lomela River (R13) and near Opala on the Lomami River (L55, L56);
- two long WSW-ENE profiles (L59-L58), calibrated by the Dekese well (1856 m deep).

All the seismic profiles with the raw seismic line, the interpreted seismic lines and the depth-converted lines are displayed in the supplementary information S1. In the following sections, we present only detailed portions of some seismic profiles which illustrate the key features of the structure and stratigraphy of the CB.

6.1 Congo River seismic profile R7-6-3-5-19

This combined seismic profile shot along the Congo River shows an alternation of highs and deep depressions (up to nearly 10 km deep), corresponding from SW to NW to the Bololo Basin, Inongo High, Lokoro Basin, Kiri High and Busira Basin (Fig. 7). Line R5, as shown in Kadima et al. (2011a), has been used to calibrate the stratigraphy of the CB using the Mbandaka well in the Busira Basin (Fig. 7c). This profile shows on the left (northern) side the full succession of the 8 seismic sequences overlying the acoustic basement in a sub-horizontal and undisturbed way. There are a series of small reverse faults affecting the Proterozoic layers below the Pan-African unconformity, while the Paleozoic to Triassic sequences are only locally dislocated by younger faults.

The highs are overlain by a regular cover of mostly undisturbed post-rift sediments, about 3 km thick over the Kiri High (Figs 7b, c), thinning over the Inongo High (Fig. 7a). Over these structural highs, the syn-rift sequences (0, 1), as well as the entire Paleozoic to Triassic sequences (4, 5) are almost absent. The rift clastics (sequence 0) are absent in the Lokoro basin, south of the Kiri High (Fig. 7b), while they reach up to 23 km thick in the Busira Basin, north to the Kiri High (Fig. 7c). In contrast, the dolomitic limestones (sequence 1) are present in the basins on both side of the Kiri High. Detailed seismic interpretation (Fig. 7b, c) suggest that the synrift sequences do not onlap against the high and/or are not condensed over its top. The sudden transitions with the adjacent Lokoro (Fig. 6b) and Busira Basins (Fig. 7c) were interpreted by Daly et al. (1992) as controlled by normal faulting during the initial failed rift stage, but the seismic profiles do not show clearly the existence of such normal faults.

Above the Kiri High (Figs. 7b, c), there are about 2 km of Neoproterozoic sediments (sequences 2 & 3), directly overlying the crystalline basement. The Red Beds (sequence 4) overly the Pan-African unconformity with a similar thickness in the Kiri High as in adjacent basins, except for the southern side, where they were probably partly eroded. The Karoo sediments (sequence 5) , which form a thick layer in all the basins, are instead only present over the Kiri High as a thin sheet on its northern side and are absent on its southern side. The Pan-African unconformity appears weakly marked and passively deformed (Figs. 7b, c). In contrast, the Basal Jurassic unconformity truncates the Paleozoic sediments over the Kiri

High and marks the expansion of the basin by regular sedimentation over the deformed pre-Jurassic part of the basin. This pattern led Daly et al. (1991, 1992) to suggest an ‘inversion’ of the Kiri High in the late Paleozoic, controlled by the pre-existing “rift” structures inherited from the initial opening of the CB. The latter would have caused uplift of the Kiri High and overlying sediments, which were partly eroded before the deposition of the Jurassic sediments. As we have no clear evidence for rift structure in the seismic profiles, we prefer to consider these structures as a product of compressional reactivation instead of inversion.

All the tectonic structures identified along the combined line remained inactive since the Jurassic, as indicated by the Jurassic to Paleogene layers lying undisturbed over the Basal Jurassic unconformity over the entire line.

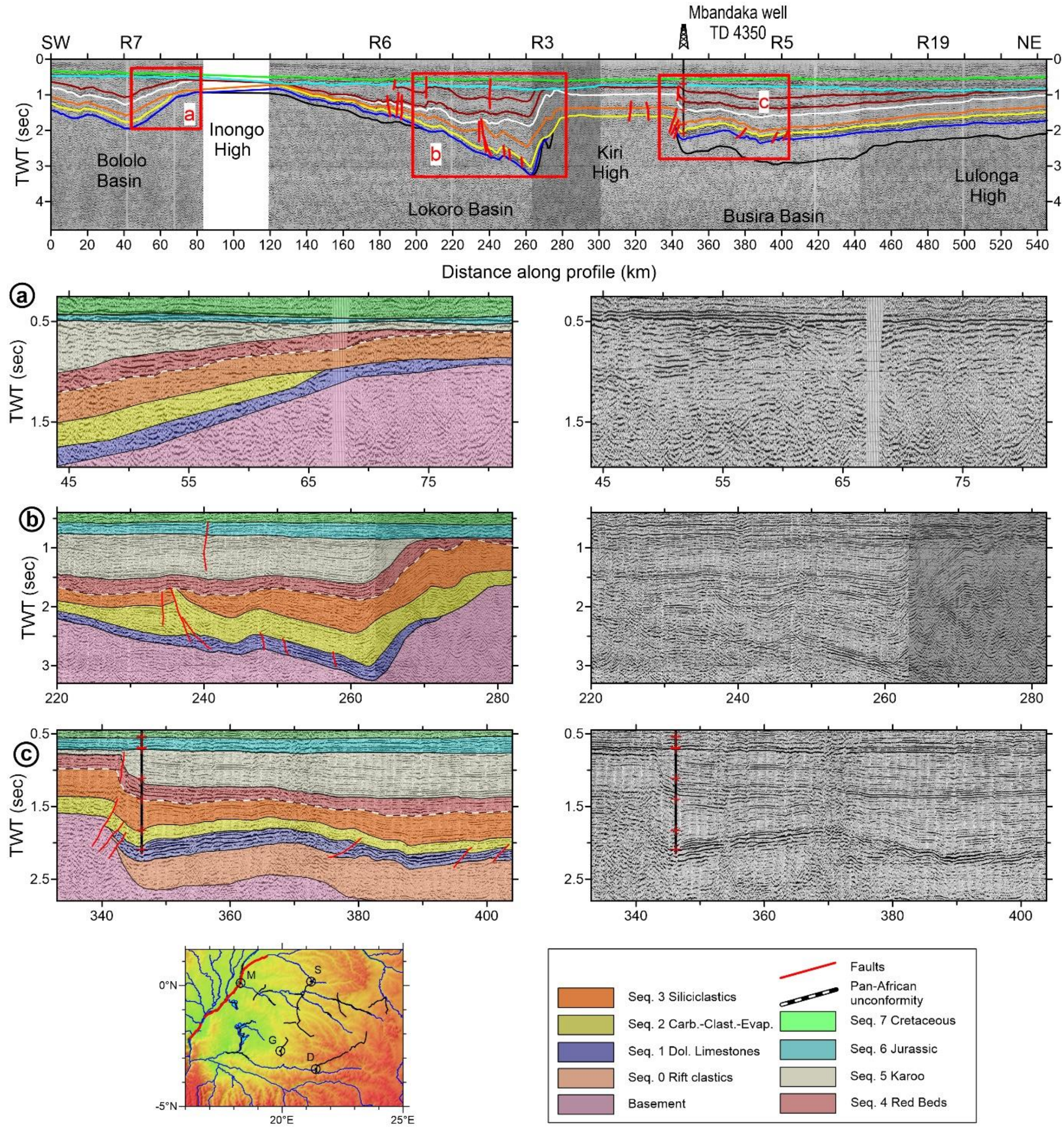


Fig. 7. Interpreted seismic profile of combined river lines R7-6-3-5-19 along the Congo River with details of three zones (a-c). Upper part: interpreted profile, a-c: details with superimposed interpretation (left) and raw profile (right). Bottom: profile location and legend. Colour of seismic horizons as in Figure 3.

6.2 Gilson-Samba seismic profile L60-50-51-52

This seismic profile with combined land lines, calibrated by the Gilson-1 and Samba wells, provides a general SSW-NNE section across the central part of the CB (Fig. 8). It shows a significant lateral variability of the depth of the basement and thickness of the sedimentary sequences up to the Basal Jurassic unconformity. There is unfortunately a gap in seismic recording in the vicinity of the Gilson well but recording was good at the Samba well.

On the southern extremity of the profile, just south of the Gilson well, a zone of tectonic deformation caused uplift of the northern compartment (with the Gilson well area) relative to the southern extremity of the profile (Fig. 8a). It affected the entire Proterozoic and Paleozoic series causing a general bending of the Pan-African unconformity, amplified by top-to-the-south reverse and thrust faulting. In contrast, the Basal Jurassic unconformity is not affected. The Karoo series appear to thicken markedly at the southern extremity of the profile. We have indicated (Fig. 8a) the possible limit between the Permian Lukuga Group and the Triassic Lueki Group, based on the interpretation of the Gilson well. However, this is poorly constrained due to the lack of biostratigraphic control (Linol et al., 2015 b) in this well.

Between km 60 and 100 along profile L60, the basement and the overlying very thin rift clastics and dolomitic limestones (sequences 0-1) are deflected downward and deepen up to a maximum depth of about 11 km (Fig. 8b). This area corresponds to an important overthickening of the Neoproterozoic series (sandstones and shales, rare limestones in the well) over a distance of 50 and 100 km along the profile. The Karoo sediments appear truncated by the Basal Jurassic unconformity.

After a hiatus in the profile, the N-trending line L50 shows an intensely folded and faulted crystalline basement and overlying Proterozoic series (sequences 0-3), truncated by the Pan-African unconformity (Figs. 8c, d). This one, in turn, has been (more locally) deformed in continuity with the deformations underneath. This illustrates the presence of well-developed Pan-African compressional structures (reverse faulting and folding) in the center of the basin and suggests also a reactivation and influence of these structures on the further evolution of the basin during Paleozoic-Triassic times (sequences 4-5). Above the Basal Jurassic unconformity, the Jurassic to Paleogene sediments (sequences 6-7) are mainly concordant with the underneath ones.

The Samba well in the northern extremity of the section (line L52) fixes the limit between the Jurassic-Paleogene sequence (sequence 6) and the Red Beds (sequence 4) at 1167 m, since the Karoo (sequence 5) is entirely missing. The red sandstones present until the well bottom (2038 m) represent the upper part of the Red Beds (the Samba-Dekese Group as defined below). We identified a pronounced reflector just below the bottom of the Samba well which we correlate with the Pan-African unconformity recognized on the left (southern) side of line L51 (Fig. 8e). On this segment, the dolomitic limestones and overlying Neoproterozoic series are affected by thrusting deformation, truncated by a prominent reflector in continuity with the Pan-African unconformity seen in line L50 (Figs. 8c-d).

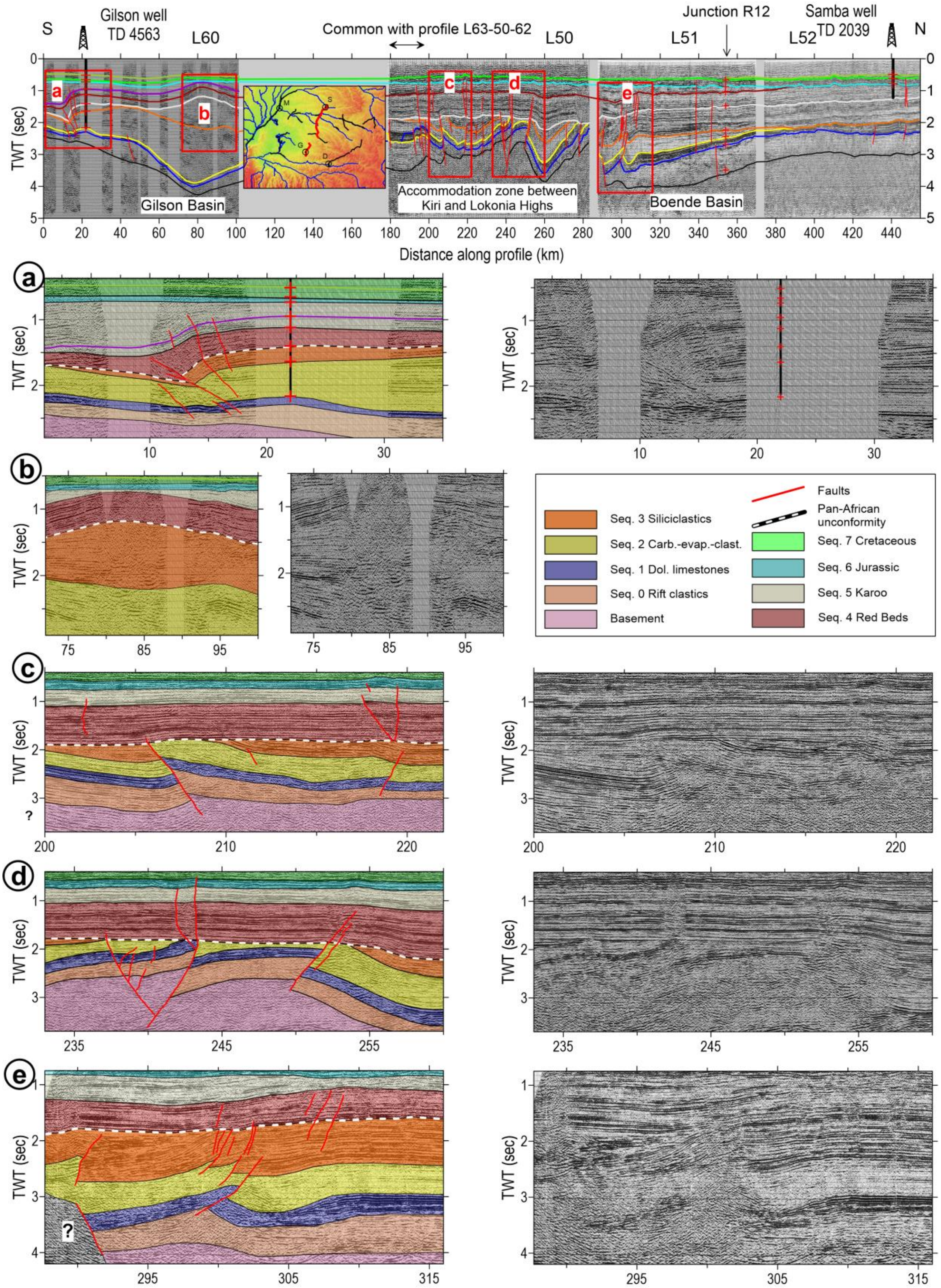


Fig. 8. Interpreted seismic profile of combined land lines L60-50-51-52 crossing the Gilson and Samba wells with details of five zones (a-e). Upper part: interpreted profile, a-e: details with superimposed interpretation (left) and raw profile (right). Insert in the general profile:

location map, Right of detail zone b: legend. Part of seismic line L50 is common with profile L63-50-62 (Fig. 9, details in 9b). Colour of seismic horizons as in Figure 4.

6.3 E-W combined seismic profile L63-50-62

This seismic profile with combined land lines cross-cuts the previous one in a general E-W orientation (Fig. 9), with part of line 50 in common with profile L60-50-51-52. It shows the Pan-African unformity truncating the entire Proterozoic sequences (sequences 0-3). The Neoproterozoic sequences (sequences 2-3) are present only in the central part, as a large and flat depression. On the western side, the Red-Beds (sequence 4) rest directly over the basement (Fig. 9a), and over the late Mesoproterozoic dolomitic limestones (sequence 1) on the eastern side (Fig. 9c). The rift clastics (sequence 0) are particularly well developed in the central part of the profile and seem to strongly thicken on the SE extremity of line 62. Here, the deep reflectors are not so clear, but we see around 120 km along the profile, an upwarp deflection of the seismic reflector which then deepens strongly until 130 km (Fig. 9c). This implies that there should be a deep depocenter (Salonga Basin) that developed during the initiation of the basin and accomodated a great thikness (4-5 km) of rift clastics.

In line L50, the dolomitic limestones layer appears slightly deformed by fault-assisted kinking (Fig. 9b). This deformation does not affect the Pan-African unconformity, but some possible faulting could also exist above it, in the Red Beds and the Karoo.

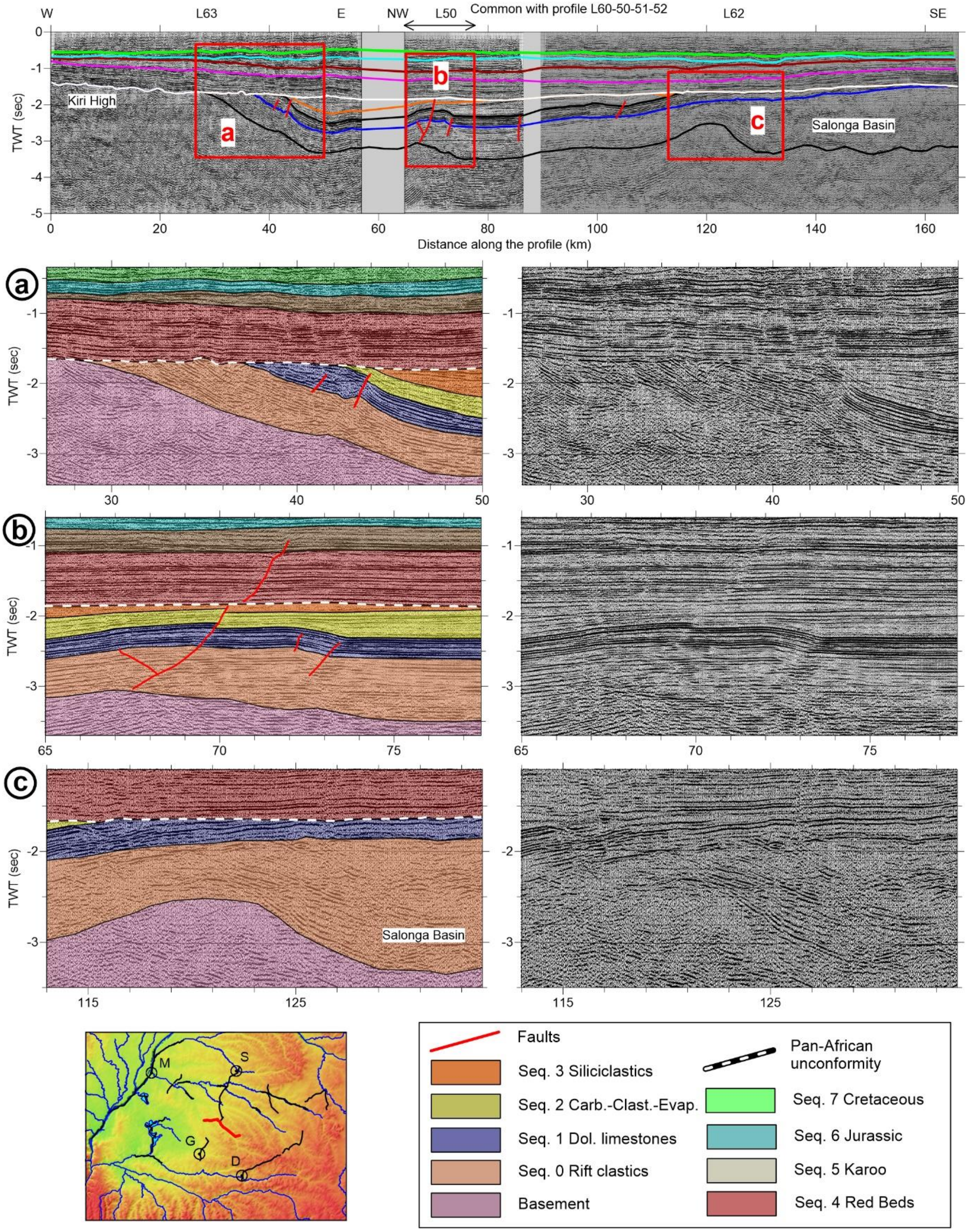


Fig. 9. Interpreted seismic profile of combined land lines L63-50-62 with details of three zones (a-c). Upper part: interpreted profile, a-c: details with superimposed interpretation (left) and raw profile (right). Bottom: location map and legend. Part of seismic line L50 is common with profile L60-50-51-52 (Fig. 8). Colour of seismic horizons as in Figure 4.

6.4 Dekese seismic profile L59

This WSW-ENE oriented profile, located in the southeastern part of the CB (Fig. 10), passes through the Dekese well. The rift clastics reach a thickness of more than 2.5 km in proximity of the Dekese well (Fig. 10a). This depocenter, named Dekese basin, reaches a maximum depth of about 8 km. Between 100 and 130 km along the profile, the Pan-African unconformity truncates the folded Neoproterozoic sequences (Fig. 10b). Some small-scale compressional deformation (folds and reverse faults) affects the carbonate level (sequence 1), suggesting it behaved during deformation as a mechanically strong layer between weaker layers (km 140-150 long the profile, Fig. 10b).

The Dekese well, on the SW edge of the profile, is located in a highly perturbed zone of the profile, most likely corresponding to a zone of intense tectonic deformation (Fig. 10a). The drill cores of the well show locally intense deformation by folding and faulting, mainly in the Karoo sequence, where some large parts reach verticality. These deformation signs have sometimes been interpreted as due to glacio-tectonic movements (Giresse, 2005; Linol et al., 2015b), but a detailed re-examination of the structures in the cores suggests rather a tectonic origin (Delvaux et al., 2015). It caused also the uplift of the northern part relative to the southern part, involving the basement as seen in the southern extremity of line L60 near the Gilson well.

The syn-rift sediments (sequences 0-1) are reduced to a thickness of few hundred meters in the SW side of the profile (toward the Kasaï craton). They seem partly eroded under the Pan-African unconformity on NE side (Lokonia High). The sedimentary sequences deposited above the Pan-African unconformity appear almost undisturbed.

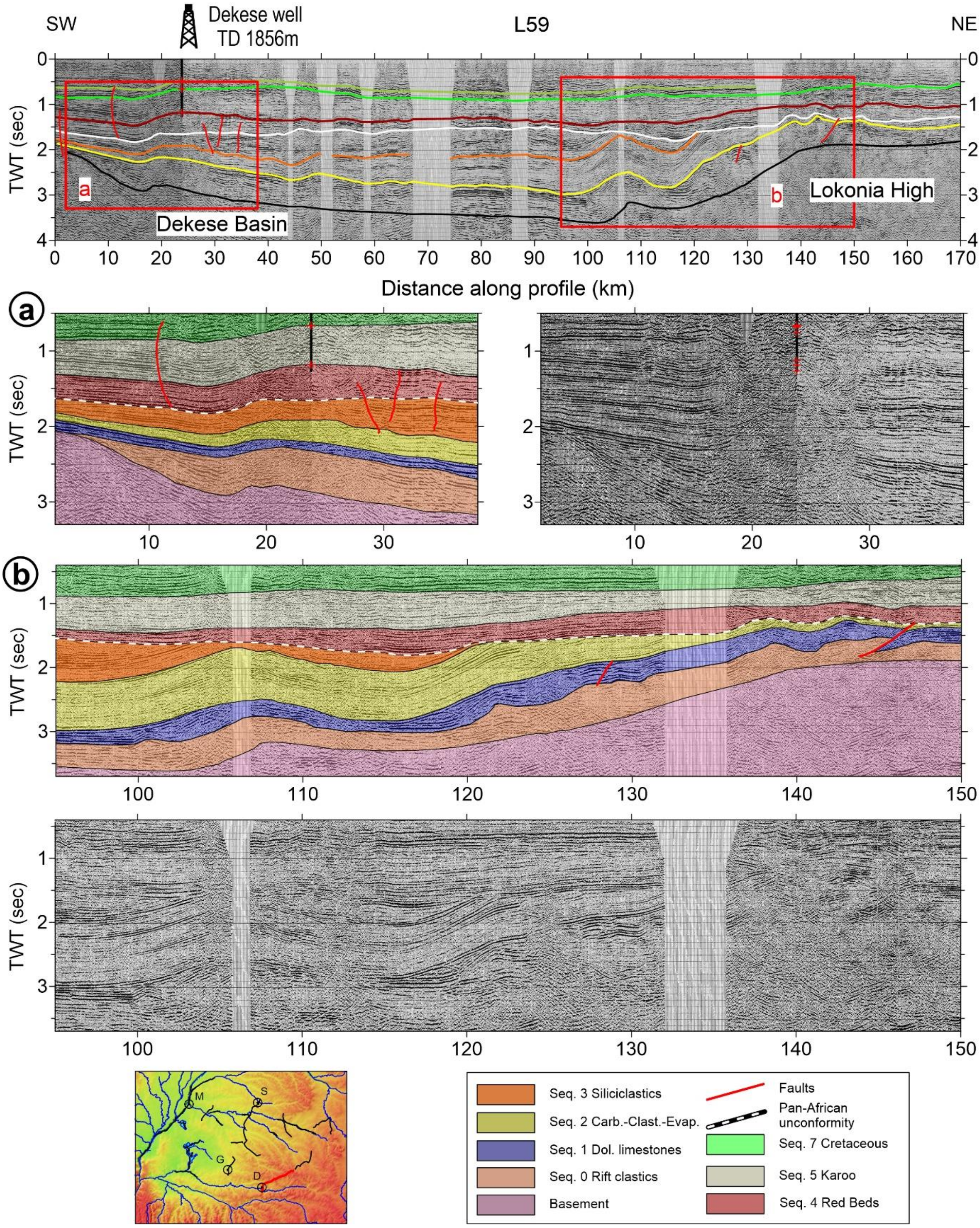


Fig. 10. Interpreted profile of land seismic lines L59 trough the Dekese well, with details of two zones (a-b). Upper part: interpreted profile, a-b: details with superimposed interpretation (left/above) and raw profile (right/below). Bottom: location map and legend. Colour of seismic horizons as in Figure 4.

6.5 Tshuapa River seismic profile R15-9-10-16

This combined WNW-trending profile of rivers lines (Fig. 11) is located in the northeastern part of the CB, along the Tshuapa River between Boende and Ikela. It shows a long-wavelength anticlinal folding of the entire Precambrian-Paleozoic series (sequences 0-5), which appears regularly stratified. The anticline forms an elevation (Maringa Ridge), which has been truncated by the Basal Jurassic unconformity. It extends laterally in the direction of the L53 and L54) seismic lines and thus has a NNW-SSE axis. The southeastern flank of the anticline shows minor faults and reverse faults in the dolomitic limestones level (sequence 1). In the central and southeastern part of the profile, the sedimentary sequences lie horizontally undisturbed, forming the Lomami basin.

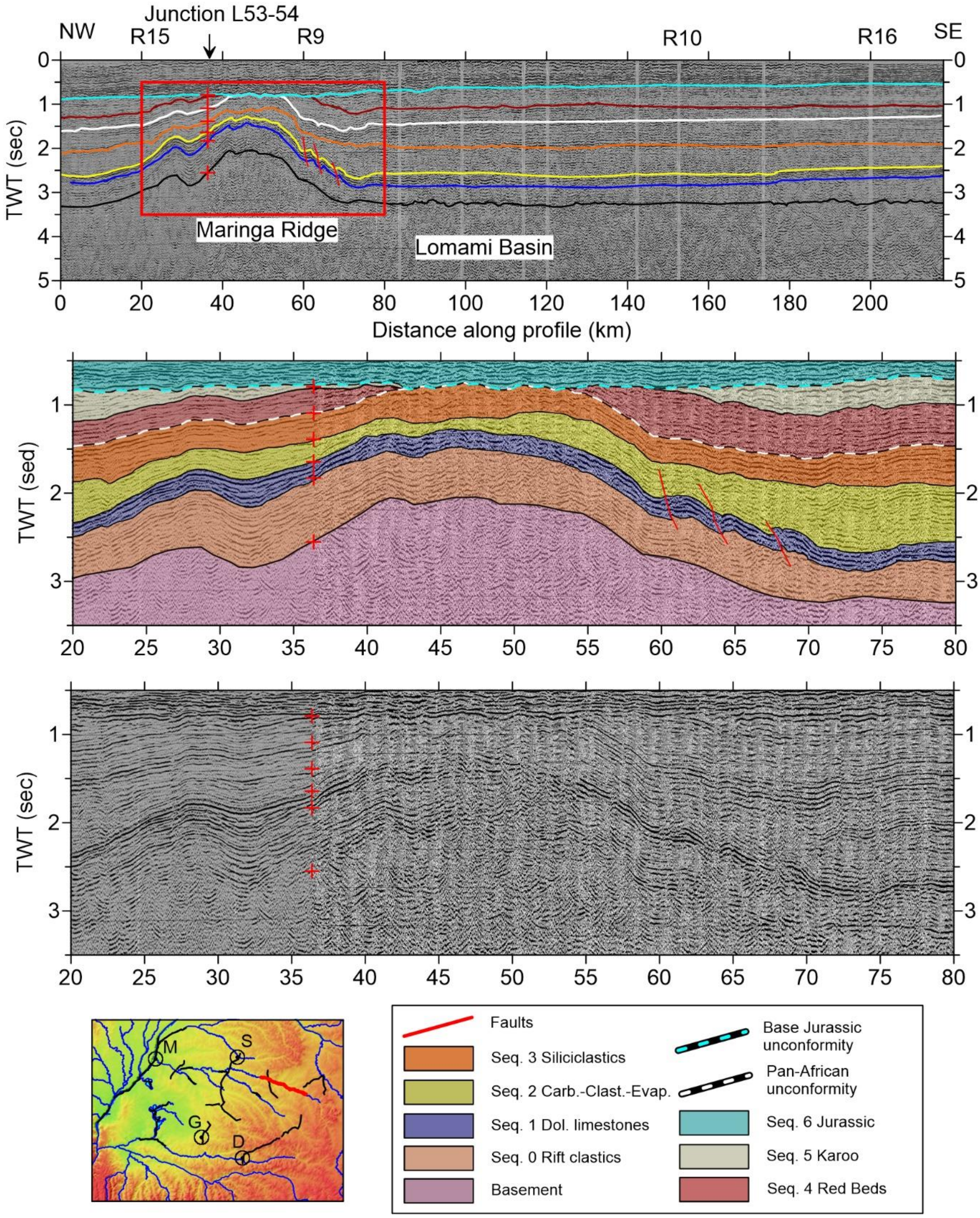


Fig. 11. Interpreted seismic profile of composite river lines R15-R9-R10, with detail of the zone around the Maringa Ridge anticline. Upper part: interpreted profile, middle part: details with superimposed interpretation, lower part: raw profile. Bottom: location map and legend. Colour of seismic horizons as in Figure 4.

6.6 Lake Mai-Ndombe seismic profile R22

Along Lake Mai-Ndombe in the southern part of the CB, the NNE-trending line R22 (Fig. 12), shows a northeastward deepening of the basement from about 3.5 to 6.5 km and of the overlying sedimentary sequence. In the northeastern part of the profile, until the junction with line R21b, we observe a pattern of small faults dislocating the late Mesoproterozoic dolomitic limestones (sequence 1) and overlying Neoproterozoic sediments, while the sedimentary sequences above the Pan-African unconformity lie undeformed. This suggests that the carbonates layer formed a more competent layer relative to the surrounding ones during the Pan-African deformation.

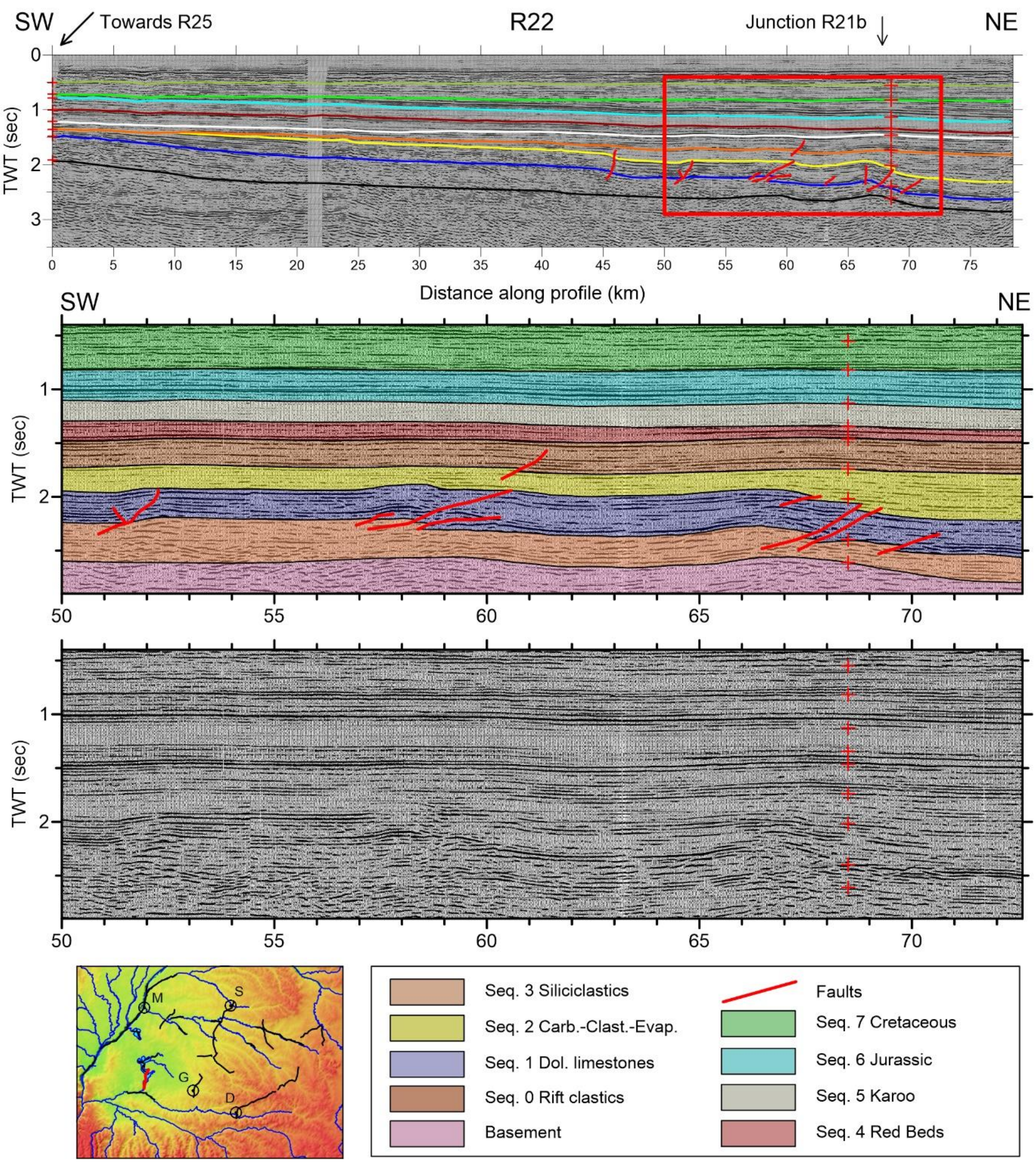


Fig. 12. Interpreted profile of land seismic line R22 with detail of the deformed dolomitic limestones sequence. Upper part: interpreted profile, middle part: details with superimposed interpretation, lower part: raw profile. Bottom: location map and legend.

7. Model of the sedimentary sequences of the Congo Basin

All the interpreted seismic horizons converted to depth were interpolated using a standard kriging method (SURFER, Golden Software package) with a grid spacing of 0.05 degree (about 5.5 km) to generate depth maps of the main seismic horizons, R0-R5 & R7 (Figs. 13, 14). The R6, R8 and R9 seismic horizons, dividing the Karoo and the Mesozoic, have not been recognized in all seismic lines and thus have not been computed. The thickness of the seismic sequences (isopach maps) has been further derived by making the difference between the depth maps of the top and bottom layers. They were computed for each sequences (S0 to S7, Fig. 15) and for groups of sequences obtained considering the 4 main stages of evolution of the basin (S0-1, S2-3, S4-5 and S6-S7, supplementary information). They reveal a different behavior of the basin during the successive stages of evolution, with a progressively decrease in the influence of the initial rift structure.

Both depth and isopach maps are limited to the data available, between 1.4°N-3.8° S, 16°E-24.5°E.

7.1 Top of basement architecture and main sedimentary depocenters

The top of the basement depth (reflector R0) shows significant variations, with major and minor elevated zones, alternated by several sedimentary depocenters (Fig. 13). The WNW-ESE Kiri High, well expressed between the Congo River and Line 63 in the center of the basin, separates the CB into two parts. It appears formed by two domes, in the places constrained by data, separated by a saddle, where there are no data. We interpret this last feature as an artefact of the interpolation and assume that the Kiri High is probably a continuous high between the Congo River and Line 63. In the eastern side of the basin, the Lokonia High appears in a similar orientation as the Kiri High, but with a shift to the north.

The relay zone between the two is illustrated by the intensely deformed seismic line L50 Line (Fig. 8).

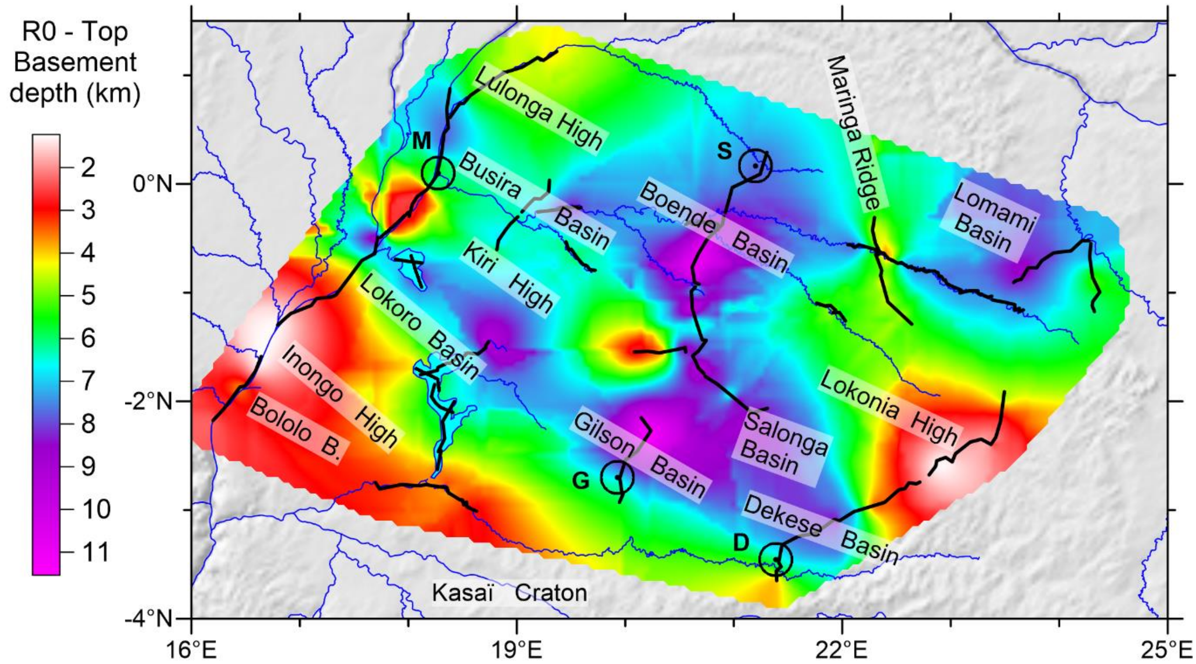


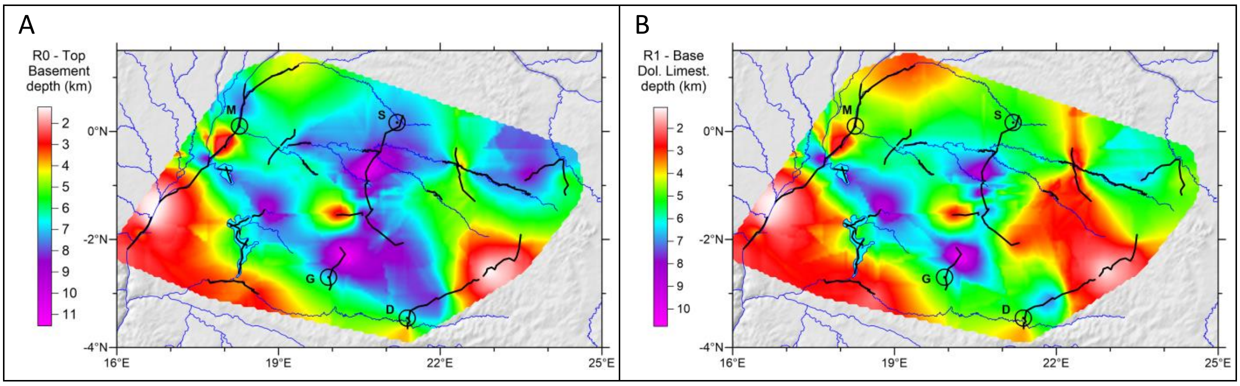
Fig. 13. Main tectonic structures identified at the depth of the top of the basement. Broken white lines show location of the seismic reflection profiles. Black circles show the location of the four wells drilled in the study area: D= Dekese; G=Gilson-1; M=Mbandaka-1; S=Samba.

The NW-SE oriented central elevated zone, formed by the Kiri and Lokonia Highs, separates the CB into two major depocenters. On the SW side, the depocenter is defined by a continuous alignment of three basins (Lokoro, Gilson, and Dekese Basins), with a maximum depth of 11.5 km observed in the Gilson Basin. It is limited to the SW by the Inongo High and, further to the south, by the Kasaï craton, which rises below the Karoo to the Cretaceous cover. The Lokoro Basin is composed of two main depocenters, one very large in the south (~ 10 km deep) and another smaller and shallower (~ 8 km deep) in the north. The deep Salonga Basin lies in the alignment of the Kiri High, after the relay zone between the Kiri and Lokonia Highs.

On the northern side of the axial zone, the Busira Basin (7.6 km deep) is flanking the Kiri High. The large Boende basin (10.6 km deep), well evidenced in the seismic line L51, is separated from the Gilson Basin by the Kiri High - Lokonia High relay zone. The Lomami Basin (8.6 km deep) on the NE extremity is separated from the Boende Basin by the Maringa Ridge. The latter appears to result from an anticlinal folding, followed by erosion of the whole pre-Jurassic series before the deposition of the Jurassic-recent series (lines R15-9-10-16, Fig. 11). The Boende and Lomami Basins could therefore have been formed initially as a single large basin.

7.2. Evolution of the depocenters with time

The results of the interpolation of the seismic reflection profiles for the different seismic horizons show the migration of the depocenters from the Proterozoic to Jurassic times (Fig. 14) and the lateral thickness variations of the different sedimentary layers (Fig. 15). They reveal a different behavior of the basin during the successive stages of evolution, with a progressive decrease in influence of the initial rift structure.



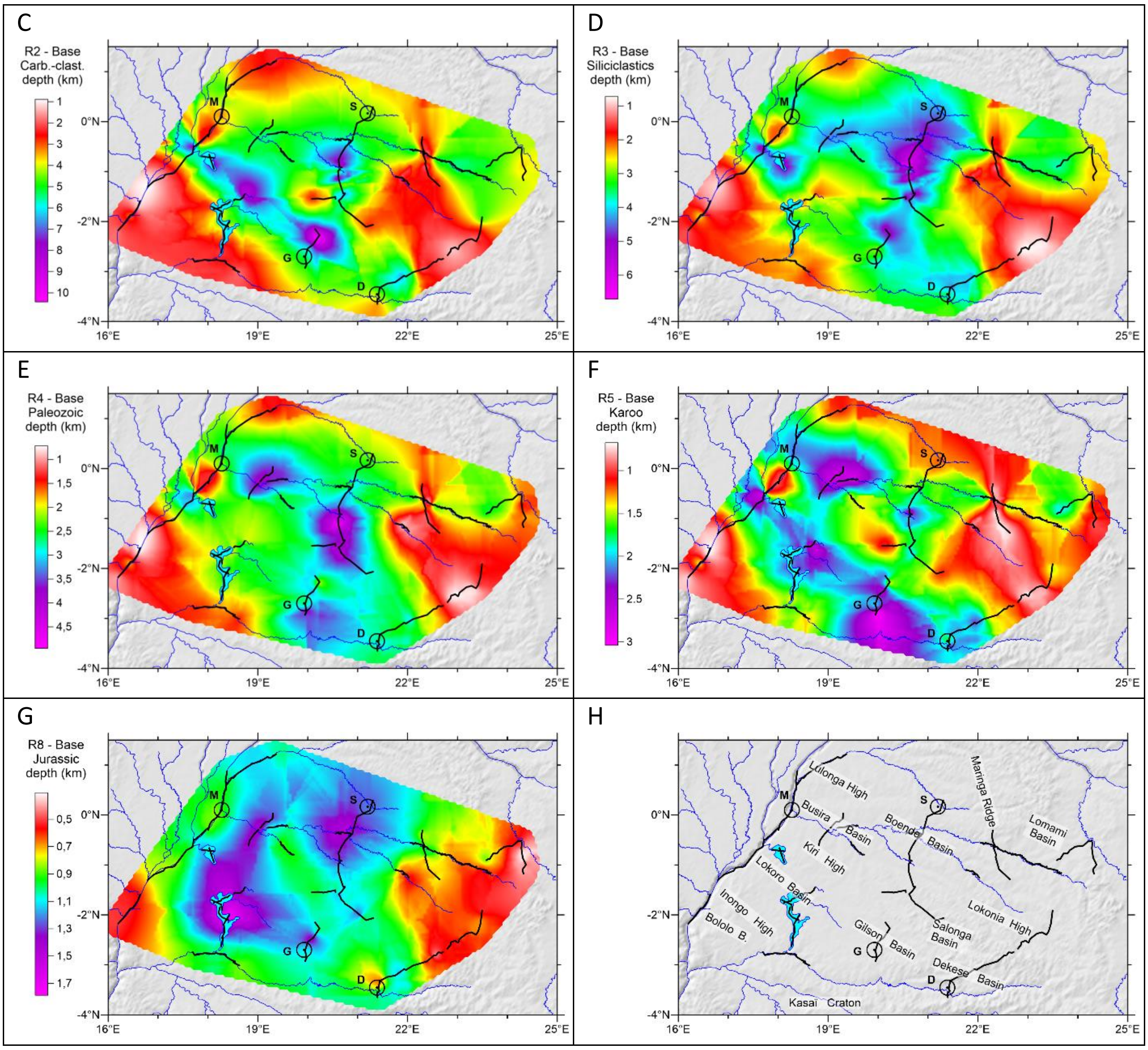
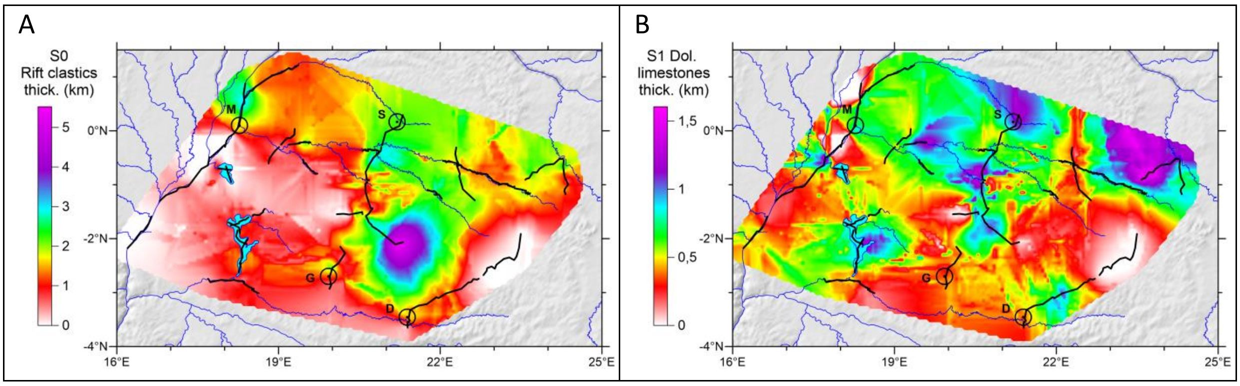


Fig. 14. Depths maps of the main seismic horizons (A-G). Names of the CB structures (H). Broken black lines show location of the seismic reflection profiles.



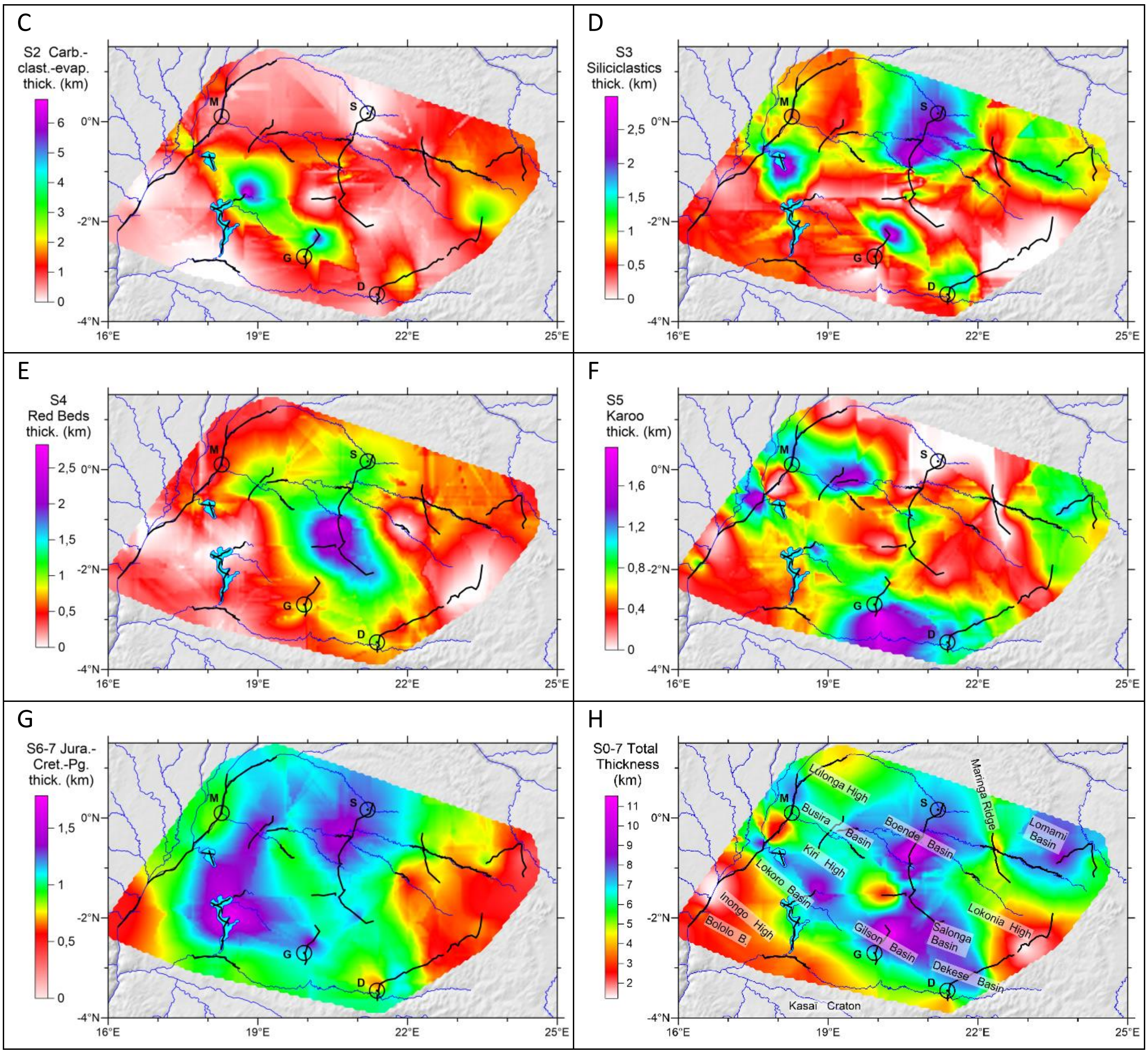


Fig. 15. Thickness maps (isopach) of the main stratigraphic sequences (A-G) and of the total sedimentary fill, with the names of the CB structures (H). Broken black lines show location of the seismic reflection profiles.

7.2.1 Late Mesoproterozoic rifting (sequences 0 and 1)

Sequences 0 and 1 (Fig. 15A, B) have been proposed to correspond to the initial failed rift stage, of possible late Mesoproterozoic age. The Kiri High is devoid of late Mesoproterozoic sediments, as shown by the seismic line R3 (Fig. 7b) and the western half of line L63 (Fig. 9a). Between these two lines, we assume a similar situation, even if the interpolation suggests some sediment. As explained above, this might be an artefact of the interpolation. This indicates that the Kiri High appeared during the rifting stage of the CB. It separates the basin into two large depressions from the beginning of its history. Globally, the CB is asymmetric at this stage, with the northern depression deeper than the southern one. The Kiri High extends laterally to line L63 in the center of the basin and forms a left-stepping relay with the Lokonia High (Fig. 13).

The rift clastics (sequence 0) are thicker in the northern part of the CB, immediately against the Kiri High, and become especially thick north of the Mbandaka well, in the Busira basin. South of the Kiri High, the rift clastics are present as a blanket in the region of Lake Inongo (group of profiles R21-25). The over-thickening in the Salonga Basin appears to be caused by important subsidence at the time of deposition of the rift clastics, close to the relay zone between the Kiri and Lokonia highs.

The Dolomitic limestones (sequence 1) are absent over the Kiri and Lokonia High and have a relatively constant thickness over the rest of the basin, fluctuating between 0.5 and 1 km. They have their greatest thickness in the northern part of the basin where they reach up to 1.6 km.

7.2.2 Neoproterozoic post-rift evolution (sequences 2 and 3)

During the Neoproterozoic, the geography of the basin changed and new basins developed. Sequences 2 and 3 (Fig. 15C, D) are the thickest in the southern depressions (Lokoro and Gilson basins), close to the Kiri High and also in the Boende Basin. The Lokoro Basin accumulated up to 6 km of carbonates-clastics (sequence 2) and the Gilson Basin, up to 5 km (Fig. 15C). The Boende Basin started to develop during the deposition of the siliciclastics (sequence 3), and the two others (Lokoro and Gilson) continued to accumulate sediments with about 2.5 km in all the tree basins, Fig. 15D). The rest of the CB accommodated a much less thickness (about 2 km), with a maximum of 3.2 km in the Lomami basin and a similar thickness over the Kiri High and the Busira Basin north of it (line R5, Fig. 7c). Over the Kiri High, they cover directly the basement (Line R3, Fig. 7b). The depocenter of the Lokoro basin fluctuated in time, with the deepest part on the eastern side (line R24) during deposition of sequence 2 and then in the western side (Lake Tumba), during deposition of sequence 3 (Fig. 14C-D).

The post-rift sequences are locally not present over the eastern extremity of the Kiri high (Line 63; Fig. 9a) and some parts of the Lokonia High (Line 59, Fig. 10b) and the Salonga Basin (line L63, Fig. 9). They might have been deposited and removed after the Pan-African deformation, as the Pan-African unconformity truncates the entire Proterozoic sequences.

7.2.3 Paleozoic post-orogenic and deglacial sedimentation (sequences S4 and S5)

After the Pan-African orogenic period, the configuration of the CB changed drastically. During the deposition of the Red Beds (sequence 4; Fig. 15E), the depocenter migrated towards a central NW-SE oriented depression, open towards the north. This depression, centered on lines L50, L60, L62 & L63 (Fig. 8, 9) lies between the Boende and the Gilson basins, with a maximum of 2.8 km of sediments. During the Karoo period (sequence 5; Fig. 15F), depocenters developed between the Gilson and Dekese wells in the south (1.97 km deep), against the Kasaï Craton and in the Busira and Lokoro basins on both sides of the Kiri High. Little sediments were deposited in the area of the former depocenter of the Red Beds. No angular unconformity can be observed on the seismic profiles between the

Red Beds and the Karoo sequences. Instead, as mentioned above, we observe a sedimentary hiatus with evidence for erosion in the transition between these series in the Dekese well at 1677 m deep.

7.2.4 Jurassic-Cretaceous transgressive cover (sequences S6-S7)

The late Jurassic-Cretaceous-Paleogene sequences (6-7) form a transgressive cover over the Basal Jurassic unconformity (Fig. 15G, H). Sedimentation was no more influenced by the initial rift structure. The depocenter of the CB now lies in the region of Lake May Ndombe with a maximum of 1.8 km of sediments (group of lines L21-24). It extends across the Kiri High towards the in the Busira basin (lines L64-65). Another depocenter developed over the Boende Basin (lines L51-52 and R12), with a maximum of 1.4 km of sediments.

8. Tectono-stratigraphic evolution of the CB

The CB had a long-lived evolution in an intracontinental setting at the center of the Congo Craton that stabilized during the Mesoproterozoic. Since then, it recorded a long geological history driven by global processes (plate tectonics and climate change) with several episodes of basin subsidence and sedimentation in intracontinental settings, interrupted by tectonic and erosional events (Pan-African near field, Gondwana far field). Sedimentation was also controlled by global climatic fluctuations and affected by several Ice House events.

Our study confirms the subdivision of the stratigraphy of the CB into three major units, representing the Proterozoic, Palaeozoic-Triassic, and the Jurassic-Cretaceous sediments (Kadima et al., 2015). They are separated by two major tectonic unconformities at the Neoproterozoic-Palaeozoic transition (related to the Pan-African deformation) and at the Triassic-Jurassic transition (related to far-field intraplate compression).

The initial rift and post-rift phases in the Meso- and Neoproterozoic produced significant subsidence of the basement in the northern part of the basin, where it currently reaches an average depth of 7-8 km (Fig. 13). In most of this area, the sedimentary sequences appear unaffected by successive tectonic events and the basement depth is sub-horizontal or shows small undulations, likely reflecting inherited heterogeneity. In the same area, the syn-rift clastics and carbonate ramp layers are well developed and reach in total an average thickness of 3 km. The overlying Proterozoic sediments reach a thickness of 4-5 km (Fig. 14C-D).

The thickness maps of the main stratigraphic units show that the migration of the depocenters with time was clearly influenced by the WNW-trending Kiri basement High, and to a lesser extent, the Lokonia High which are considered to be the axial zone of the paleorift (Kadima et al., 2011b) that separates the CB into two parts (Fig. 15). The Kiri High had a strong control on the sedimentation and basin architecture during the late Mesoproterozoic and Neoproterozoic. This control weakened during the Palaeozoic and Mesozoic.

The basin sedimentation and structure have been further influenced by global climate fluctuations (ice/greenhouse ages), the paleo-geographic position of the CB (South Pole to the Equator), as well as by tectonic phases (folding and thrusting) and local/regional denudation stages.

8.1 Late Mesoproterozoic basin initiation

The age of initiation of the CB remained controversial for a long time, but tends to get older with the increasing geological knowledge and data analyses. It was initially considered to be Carboniferous to recent (Veach, 1935; Cahen, 1954; Lepersonne, 1977), as these authors considered that the pre-Carboniferous sediments were part of the “Congo platform cover”. After integration and synthesis of the results collected during the second exploration campaign, and by correlation with the Lindian studied by Verbeek (1970), the CB was considered to be Neoproterozoic in age (Chorowicz et al., 1990; Daly et al., 1991, 1992) More recently, Delpomdor et al. (2013b) correlated the basal series of the CB, within the failed rift basin of Kadima et al. (2011a), with the Mbuji-Mayi Supergroup, which could represent its outcropping southeastern prolongation. We also support this correlation, but Delpomdor et al. (2013b) puts the age of the of BII group of the Mbuji-Mayi Supergroup between 750 and 880 Ma, contemporaneous with the break-up of Rodinia and the initiation of the Katanga basin (Cailteux and de Putter, 2019). However, François et al. (2017) dated the Mbuji-Mayi Supergroup between 1065 and 1000 Ma, (Stenian, Upper Mesoproterozoic), thus before the main collisional events at about 1000 Ma that led to the Rodinia supercontinent assembly (Li et al., 2008). The initiation of the CB could therefore be contemporaneous with the Taoudeni Basin (Martin-Monge et al., 2016; Beghin et al., 2017a, 2017b). It cannot be

related to the initial Neoproterozoic divergence that occurred along the southern margin of the CB, recorded in the Zambezi and Lufilian basins belts between 880 and 820 Ma (first rift cycle of de Waele et al., 2008).

Four main depocenters where the basement reaches very large depths between 9 and 11 km have been identified. The Lokoro Basin and the combined Gilson, Dekese and Salonga Basins flank on the southern side the Kiri and the Lokonia Highs while the Boende and Lomami Basins flank these highs on their northern side. The latter two could have formed initially as a single large basin, now disrupted by the Maringa Ridge. This alternation of highs and deep basins, NW-SE oriented, is already known since the time of the first explorations in the CB (e.g., Cahen, 1956; Kadima et al., 2011a), but we identified now new basins such as the Dekese and Salonga Basins with a total sedimentary infill of about 7 km. The difference in the shape of the basins and thickness of the syn-rift sequences can be attributed to a non-uniform syn-rift extension, which affected more the northern than the southern part of the CB. Another hypothesis is that inherited heterogeneity of the basement, derived from different cratonic nuclei, influenced the shapes and sizes of the basins formed in response to uniform (or non-uniform) extension, as well as the thickness of syn-rift sediments. This would explain the great thickness of syn-rift sediments in the Salonga basin, relative to the Lokoro and Gilson basins, which are almost devoid of them.

The paleorift structure is represented by the Kiri and the Lokonia Highs, which act as basement uplifts between opposed diverging monoclines. They were not covered by the rift clastics (sequence 0), nor by the dolomitic limestones (sequence 1), but by the post-rift sediments (sequences 2-3). They represent two offset highs, instead of a continuous rift structure, as proposed by Kadima et al. (2011a, b).

8.2 Neoproterozoic evolution (Rodinia to Gondwana)

New depocenters formed during the Neoproterozoic in the CB (Lokoro, Gilson and Boende basins), filled by sequences 2 and 3 in a relatively continuous sedimentation. No regional unconformity can be seen between these two units, which are sometimes difficult to distinguish in the seismic profiles. The apparent continuity in sedimentation also suggests that no tectonic events disturbed the basin. The general geodynamic conditions of the CB were that of a relatively stable intracontinental setting, probably in a general extensional context. It is difficult to invoke post-rift subsidence for the entire period (nearly 500 Ma) as during that time, complete Wilson-cycles occurred along the margins of the Congo Craton, in the West-Congo belt (Pedrosa-Soares et al., 2008), Damara (Gray et al., 2008) and Katanga

(Lufilian) belts (Cailteux and De Putter, 2019), and possibly also along its south-eastern margin, in the Ubende belt (Boniface and Appel, 2017; Fig. 2).

8.3 Pan-African deformation and unconformity

Daly et al. (1991, 1992) already evidenced a distal effect of the late Paleozoic peri-Gondwana orogenies as major contractional deformation observed in the seismic profiles. Our analysis of the profiles reveals that the Pan-African orogenies that developed around the Congo Craton at the end of the Neoproterozoic, also caused locally intense far-field deformations in the CB. They are even better expressed than the late Paleozoic deformations in the center for the CB, as shown by profile L50 (Fig. 7) and L63-L62 (Fig. 8). The western extremity of profile L63 (Fig. 8a) shows that the entire Proterozoic succession has been eroded away before the deposition of the Paleozoic series over the Pan-African unconformity.

In several profiles, such as R5 (Fig. 7c), R9 (Fig. 11) and R22 (Fig. 12), the dolomitic limestones (sequence 1), which is marked by strong parallel reflectors, is affected by reverse faults that disappear in the adjacent sequences below and above.

At the periphery of the basin, the Mbuji-Maji series are folded and faulted at the contact with the Kibara belt in the Katanga region, in the area of the Lomami River (Cahen and Mortelmans, 1947). This deformation has been interpreted as a far-field effect of the Lufilian orogeny which could have reactivated the Kibaran structures.

8.4 Paleozoic Gondwana Super-fan

The compressional tectonics that led to the formation of the Gondwana continent was followed by post-orogenic extension and denudation (removal of several km of sediments) in the early Paleozoic, with consequent development of the of the Pan-African tectonic and erosional unconformity during the Cambrian (Lucazeau et al. 2015).

The seismic sequence 4, interpreted to represent the Red Beds, shows a well-defined depocenter in the middle of the basin, opened towards the north and terminating towards the South in the region of the Dekese well, against the Kasaï Craton (Fig.15E). This sequence was not observed over the Kasaï craton (Roberts et al., 2015). These Red Beds be the extension into the CB of the Cambrian-Ordovician North Gondwana Super-fan System of quartz-rich sandstone (Squire et al., 2006; Meinhold et al., 2013; Lewin, 2020). Quartz-rich arkosic sandstones are known to have been deposited during the Cambrian-Ordovician times in Northern Africa and the Arabian Peninsula (Burke et al., 2003; Avigad et al., 2005; Squire et al., 2006). They originate from Pan-African terranes exposed by post-orogenic uplift and chemical weathering of the Transgondwanan Supermountain (Squire et al., 2006) of the East African – Antarctic Orogen (Fritz et al., 2013) that developed between East and West Gondwana.

This enormous depositional system of continent derived sediments throughout Gondwana lasted at least 260 Ma, from late Cambrian to early Devonian (Squire et al., 2006). These sediments are characterized by typical detrital zircon age spectra with a prominent double peak at 550-650 Ma (dominant) and 900-1200 Ma (secondary), with a minor Paleoproterozoic contribution. Using this pattern, Squire et al. (2006) proposed that the post-530 Ma sediments deposited over the Kuunga Suture, between the Congo and Kalahari cratons (Damara and Katanga belts), could also be originating from the East African orogen.

The Red Beds in the Samba well in the CB have also detrital zircons with two major peaks, at 560-830 Ma and 930-1160 Ma, and minor peaks at 1.2-1.5 Ga and 1.9-2.1 Ga (Linol et al., 2015b). This unit is considered the equivalent to the similar red arkoses of the Dekese well (Cahen et al., 1960), which are below the Permo-Triassic series, but Linol et al. (2015b), without further data, considered them as Triassic. The small contribution of Ectasian-aged zircons (1.3-1.4 Ga) indicates that the Karagwe-Ankole and Kibara belts on the eastern margin of the CB (Tack et al., 2010; Fernandez-Alonso et al., 2012) cannot be an important source for these sediments. Similarly, as the Paleoproterozoic-aged zircons are also rare, a contribution from the Ubende and Rusizi belts (Lenoir et al., 1995) is also minor if any. A sample of red arkoses from the Red Beds sequence at the bottom of the Dekese well (1853 m deep) was also studied (Linol et al., 2016), providing a similar detrital zircon pattern, with major peaks, at 610-830 Ma and 880-1100 Ma, respectively, and minor peaks, at 2.0-2.1 Ga and 2.4-2.6 Ga, respectively. This is a further argument to support a lateral correlation between the red arkoses encountered in the lower part of these two wells.

We propose here that the Red Beds (sequence 4) of the CB could at least partly have been fed by the erosion products of the Transgondwanan Supermountain coming from the East African – Antarctic Orogen. They could represent the extension of the Gondwana Super-fan System in Central Africa, as giant distal sedimentary fans in major intracontinental basins, as already proposed by Squire et al. (2006). The morphology of the sequence 4 unit, stopping against the Kasaï Craton in the south, suggests an origin of the fan in the CB from the north.

Along the margins of the CB, Red Beds are known as the red arkoses of the Banalia Group which crop out on the northern margin of the CB (Verbeek, 1970) as those of the Biano group in the Katanga fold belt (Cailteux and Deputter, 2019), but no detrital zircon data are available for these units. The red arkoses of the Inkisi Group in the West-Congo belt contain a high abundance of 500-800 Ma zircons with two major peaks, at 500-800 Ma and 900-1200 Ma and minor peaks at 1.8-2.2 Ga and 2.5-2.8 Ga (Straathof, 2011; Affaton et al., 2015), pointing to a possible origin in the Brasiliano Araçuai orogeny.

Verbeek (1970) proposed already to correlate the Banalia arkoses with the red arkoses of the Samba and Dekese wells. He noticed the common abundant presence of relatively fresh feldspar, from 40% in the Samba and Dekese wells (Cahen et al., 1959, 1960) up to 70% in the Banalia Group (Verbeek, 1970). They contain a relative importance of detrital micas, similar to the composition of granitic rocks. The arkoses are well-sorted and fine-grained, with the presence of clay pebbles. They occur in an alternation of layers with cross-bedding and parallel bedding, with intercalations of red clay layers. They contain ripple-marks and intraformational folds. These are also the characteristics of the Inkisi red arkoses, with the difference that they contain in addition well-rounded pebbles of quartz, quartzite, magmatic, and metamorphic rocks of different origin (Alvarez et al., 1995).

From the arguments given above, we consider the Banalia, Banalia and Inkisi arkoses as stratigraphically equivalent and forming lower unit within the Red Beds, overlying the Precambrian basement. The Samba and Dekese arkoses would be a stratigraphically upper unit of the same Red Beds, under the Karoo or directly the Jurassic in places (core of the Maringa Ridge). It is not clear how these series connect laterally in the CB as the biostratigraphic control is inexistant.

Building on Tack et al. (2008) and Fernandez-Alonso et al. (2015) who introduced the correlation of the Biano, Banalia and Inkisi units as a single distinct lithostratigraphic Group between the Neoproterozoic and Karoo Supergroups, we can now propose that this be expanded to incorporate all the Red Beds in the CB, defining a new lithostratigraphic supergroup that we propose to name Aruwimi Supergroup, from the name of the river where Verbeek (1975) described for the first time to the Aruwimi sequence, which forms the upper part of the his ‘Lindian’ and includes a.o. the Banalia arkoses. Indirect stratigraphic constraints show that it is broadly of Cambrian to Devonian age. It is composed the lower Inkisi-Banalia-Biano Group and the upper Samba-Dekese Group. The Inkisi-Banalia-Biano

Group is observable along the margins of the CB, as molassic deposits in the foreland of the Pan-African fold belts. The Upper Nama Group can be considered as the equivalent over the Damara belt on the SW margin of the CB in Namibia (Blanco et al., 2011). The Samba-Dekese Group is seen only in the wells drilled in the Cuvette Centrale, and particularly in the fully cored Samba and Dekese wells.

The depositional environment and provenance of the Red Beds has been already discussed by Verbeek (1970). Good sorting and find-grain imply a long-distance transport, while the freshness of the feldspars indicates non-aggressive chemical conditions. The mineralogical composition indicates a granitic source under denudation. The deposition conditions are typically continental, compatible with a large braided-river system without vegetation. The great thickness (up to 2.5 km in the CB) and homogeneity of the entire sequence of arkoses point to a long-duration and major size of the source area, compatible with the suggestion that this seismo-stratigraphic unit could represent a new branch of the Gondwana Super-fan in Central Africa. During the entire late Cambrian to Devonian, Central Africa remained in southern latitude above 40° and in relatively cool climatic conditions (Torsvik and Cocks, 2013). We found no evidence that the deposition of the Red Beds sedimentation was interrupted or influenced by the late Ordovician glaciation and ice sheet, which affected most of Northern Africa (e.g. Ghienne et al., 2007).

8.5 Karoo deglacial sequence

The CB was close to the South Pole in the earliest Carboniferous at the time of the Gondwana glaciation. Not much is left of this period in the CB, except for the depositional hiatus, which marks the transition between the Red Beds (sequence 4) and Karoo (sequence

5) in the Samba and Dekese wells. The effect of this climatic event has been recorded in the Karoo deglacial sequence, from the periglacial Lukuga unit to the post-glacial Lueki unit.

The paleogeography of the CB during the Permo-Triassic is clearly different from that of earlier stages. The marked N-S central depocenter of the Red Beds sequence is no more the dominant feature. There are no Karoo sediments in the Samba well and along the L50-52 N-S seismic lines (Fig. 8), while new depocenters appear on each side of the Kiri High, in the Busira and Dekese basins. The latter was probably part of a large intracontinental lake during the Permian deglacial period (Wopfner, 1999; Linol et al., 2015b), evolving into a warmer post-glacial basin in the Triassic. Recycled vitrinite in the sediments of the Lukuga Group (Permian) suggests their provenance from a sedimentary source, not older than late Devonian (Sachse et al., 2012). A detrital zircons profile (Linol et al., 2015b) shows the same age ranges as for the Red Beds, but with markedly different proportions. The age range 950-1150 Ma is the dominant peak, followed by the Paleoproterozoic contribution between 1.8 Ga and 2.1 Ga. These terranes are common to the east of the CB, with the ~ 980 Ma leucogranites of the Kibara and Karagwe-Ankole belts (Tack et al., 2010), the 1860-2100 Ma Ubende - Rusizi belt (Lenoir et al., 1995) and in the East African orogen (Fritz et al., 2013). A late Neoperoterozoic contribution (600-850 Ma) is the third in importance, indicating a significant contribution from the Pan-African aged terrains. Minor contributions are noticed at 1350-1450 Ma, indicating a possible contribution of the Ectasian (1370-1380 Ma) magmatism in the Kibara and the Karagwa-Ankole belts (Tack et al., 2010) and at 2.5-2.7 Ga from the Paleoproterozoic to Neoarchean basement. Overall, this detrital zircon pattern is interpreted as a dominant contribution from the glacial erosion products of the basement East of the CB, from melting ice sheets, originating from the paleo-pole position at that time (over present-day Antarctica). The reworked vitrinite observed by Sachse et al (2012) also suggests a contribution from Southeastern Africa.

In conclusion, we observe a major change in the depocenters and sediment source from the early Paleozoic (sequence 4) to the late Paleozoic-Triassic (sequence 5), even if no major unconformity is noticed between the two sequences. There might have been a sedimentation hiatus with some reworking, likely driven by global climate change, but not by major tectonic events.

8.6 Late Permian-early Triassic deformation

Late Paleozoic deformations in the CB were first evidenced by Daly et al. (1991, 1992) who described compressional reactivations of the Kiri High, controlled by the pre-existing rift structures inherited from the initial opening of the CB (lines R3-R5, Fig. 7). In the seismic line L50 (Fig. 8), the Paleozoic series and Pan-African unconformity are both deformed in continuity with the Pan-African structures that affect the Paleoproterozoic sequences underneath, suggesting their reactivation. In contrast the Basal Jurassic unconformity and overlying sediments are not affected, constraining the deformation between the end of the Permian and the late Jurassic. The timing of the deformation relative to the Triassic Lueki Group is less clear. Some deformation could have occurred before and/or after it. Line 60 calibrated by the Gilson well (Fig. 8a) would suggest that the Lueki was affected by the deformation in the Gilson Basin before deposition of the Kisangani Group (Fig. 8b).

Another expression of this deformation is illustrated in lines R15-16 (Fig. 11), where the entire Paleozoic to Proterozoic sequences were deformed in an anticlinal folding (Maringa Ridge) with a 70 km-long wavelength. This falls within the range of upper crustal lithospheric folding that typically develops in a layered lithosphere with an old thermotectonic age (> 500 Ma) submitted to horizontal compressional stresses (Cloetingh et al., 1999; Delvaux et al., 2013). The crest of the anticline has been completely eroded before the deposition of the Jurassic Kisangani series, which provide a clear age relationship.

8.7 Jurassic-Cretaceous

While the Permo-Triassic compressional event caused weaker and more localized deformation than the Pan-African deformation, it was still followed by important denudation. During the early Jurassic, up to 4000 m of sediments might have been removed as constrained by vitrinite reflectance in the Mbandaka and Dekese wells (Lucazau et al., 2015), forming the Basal Jurassic Unconformity. The latter can be observed in-situ along the Lualaba segment of the Congo River, upstream of Kisangani (Caillaud et al., 2017), where sedimentation started in an anoxic lake, producing high quality lacustrine type II organic matter (Sachse et al, 2012).

The overlying late Jurassic and Cretaceous to Paleogene seismic sequences (6 and S) cover not only the CB, but also its margins as a transgressive blanket, thus enlarging the size of the basin. Towards the south, it covers a large part of the Kasaï craton, locally over a thin layer of Karoo sediments (Roberts et al., 2015). It contains lacustrine, fluvio-lacustrine and aeolian sequences, deposited in the context of Gondwana breakup and the African plate, with a more diverse source of sediments than during the Paleozoic, as indicated by detrital zircon age provenance (Linol et al., 2015c).

8.8 Late Cretaceous-Cenozoic

As stated earlier, the CB underwent since the Late Cretaceous a new stage of erosion and denudation (Sachse et al., 2012; Lucazeau et a:., 2015) with the formation of the ‘African

Surface', the Kalahari Group and the modern landscape (Giresse, 2005; Guillocheau et al., 2015; Linol et al., 2015e).

9 Basin evolution in a broad context.

The long geological history of the CB recorded a series of tectonic and climatic events that, given the size of the basin, located centrally in the Gondwana Supercontinent, are likely of global scale. It is thus useful to correlate the evolution of the CB in the broader context of Rodinia and Gondwana. The latter is illustrated in a schematic way in Figure 16.

9.1. Congo Basin in the context of Rodinia assembly and breakup

The nucleation of the Congo Craton was completed with the "Kibaran" LIP magmatic event at around 1375 Ma in the eastern Congo Craton (de Waele et al., 2008; De Bruyne et al., 2015; Fernandez-Alonso et al. 2015). As the CB initiated during the final stages of the Rodinia Supercontinent amalgamation around 1 Ma, its geodynamic evolution can be put in parallelism with that of the Western Domain of the Karagwe-Ankole Belt (WD-KAB). The latter, which is relatively well known in Rwanda (Tack et al., 2010; Fernandez et al., 2012), extends westwards into the Kivu-Maniema region in the DRC (Lagmouch et al., 2018) and further west disappears below the CB sediments where it may form the crystalline and/or metamorphic basement in its northern part (Master, 2010). The metamorphic and tectonic evolution of the WD-KAB was recently revised and put into relation with the geodynamics evolution of Central Africa (Van Daele and Scherer, 2020; Van Daele et al., 2020). The Mesoproterozoic WD-KAB evolved in the context of Rodinia assembly in a prolonged but poorly defined extensional setting, with dominant quartzo-pelitic sedimentation and episodal magmatism and metamorphism.

The oldest Mesoproterozoic sediments (Bugarama Gr.; 1420-1380 Ma) are intruded by widespread LIP bimodal magmatism, followed by dolerite dyke swarm intrusion at 1380-1360 Ma (Fernandez et al, 2012; Mäkitie et al., 2014). Sedimentation resumed after 1220 Ma (Rugezi and Cyohaha Gr.). At about 1000 Ma, a short-lived far-field fold-and thrust deformation occurred, followed by leucogranite intrusion and associated regional metasomatism and metamorphism up to 960 Ma (Fernandez et al, 2012; Van Daele et al., 2020). This marked the termination of sedimentation in the WD-KAB, which resumed in the Cryogenian (Itombwe Supergroup), just after carbonatitic magmatism, in the context of Rodinia breakup (820-750 Ma). A new phase of retrograde metamorphism and ductile-brittle deformation occurred (Van Daele & Scherer, 20200), in reaction to the East-African Orogeny (650-620 Ma and the final Gondwana assembly (580-500 Ma) (Fritz et al., 2010).

In parallel, the CB started to develop at the end of the extensional stage of the Rodinia assembly, in late Mesoproterozoic. The ca. 1000 Ma 'Rodinia assembly' event is best expressed in the Irumides belt (Fig. 1; Fernandez-Alonso et al., 2012) and also expressed in the Kibara Belt (Fig. 2; Kokonyangi et al., 2002). It corresponds to the termination of the failed rift stage of the CB, transition from the dolomitic limestones (sequence 0) to the carbonates-evaporates-clastics (sequence 1). The siliciclastics (sequence 2) are coeval with the Itombwe Supergroup in eastern DRC and both were deposited in the context of Rodinia breakup. The Pan-African deformations and major unconformity in the CB are coeval with the last phase of metamorphism and deformation in the WD-KAB.

Other Neoproterozoic basins developed over the West-African Craton: the huge Taoudeni and peripheral basins in the center and the Tindouf and Volta basins as peripheral forelands (Bertrand-Sarfati et al., 1991; Deynoux et al., 2006). Sedimentation started at about

1100-1200 Ma in the Taoudeni basin (Rooney et al., 2010; Martin-Monge et al., 2016; Beghin et al., 2017a) and formed in a pericratonic to intracratonic unstable extensional tectonic context (Bronner et al., 1980; Beghin et al., 2017b). It recorded a discontinuous sedimentation history from late Mesoproterozoic to Paleozoic, including glacial deposits and was partly influenced by the Pan-African orogenic evolution (Villeneuve, 2005; Deynoux et al., 2006). The Taoudeni basin was deformed and uplifted by the Variscan deformation and covered by thin Mesozoic–Cenozoic units and Quaternary sand dunes (Trompette, 1973; Clauer, 1981; Deynoux et al., 2006; Balukiday et al., 2018).

These basins are generally considered as intracontinental sag basins (Einsele, 1992; Allen and Allen, 2005). They form in continental interiors, affecting large areas with slow subsidence and a marked lateral continuity in the sedimentary layers. They can reach considerable thickness and remain active for long periods of time. They commonly form in the context of divergent plate motion and may have a central rift structure (Einsele, 1992). The CB with its suspected underlying failed rift is considered as one of them by Allen and Allen (2005). In the intracratonic basins, the initial failed rift likely formed by passive rifting rather than active rifting. In passive rifting, volcanism occurs during rifting and doming, as a consequence of lithospheric extension, while it occurs before in the active rifting model (Frizon de Lamotte et al., 2015).

The Mbuji-Mayi Supergroup, which is considered as a proxy for the hidden rift below the CB, shows effectively a succession of rift clastics (BI Group) and dolomitic limestones (BII Group) terminating with basaltic lavas (François et al., 2017). Such a passive style of rifting tends to develop rather wide rifts at low strain rate in a thick and warm crust instead of narrow and well-focused rifts at high strain rate for an active style (Frizon de Lamotte et al., 2015).

9.2. Congo Basin in the context of Gondwana assembly and breakup

The Pan-African structures expressed by compressional deformation in the central part of the CB (this work) can be compared with the fold-and-thrust belt that developed in the Gourma basin on the eastern margin of the Taoudeni Basin (Villeneuve, 2005; Deynoux et al., 2006). In both cases, these structures are sealed by a major unconformity overlain by Paleozoic sediments. Elsewhere, in North Africa, Arabia and South America, numerous new Paleozoic basins formed over the Precambrian basement, all influenced by global climatic and tectonic events.

The term 'Inversion' was used by the former authors (Daly et al., 1992; Kadima et al., 2011a). We recognize that this term is not fully appropriate, at least at the scale of the tectonic structures, as we cannot see precisely inverted structures in the profiles. For these, we preferred to use the term 'compressional reactivation'. Within the general intraplate context, we can eventually use the term 'inversion' but at the basin-scale, considering that the major periods of sedimentation which occurred in an general (but poorly defined) extensional context have been interrupted by relatively short periods of far-field compressional tectonic deformation.

The Paleozoic sag basins of NW Africa (Tindouf, Reggane, Ahnet, Mouydir Ilolizi/Ghadames/Jefarah, Murzuk and Kufra basins in southern Algeria, Tunisia and Libya) formed over the Sahara Metacraton with a remarkably uniform early Paleozoic stratigraphy and a strong influence of the late Ordovician Hirnantian glacial event (Ghienne et al., 2007). Their development stopped in the Carboniferous as a consequence of the Variscan orogeny, before a new Mesozoic evolution (Selly, 1997; Jabir et al., 2020).

The Great Arabian Basin recorded a history of sedimentation influenced by global climatic changes and tectonic movements from the Cambrian to the Triassic, with the major late Ordovician glaciation and Taconic (late Ordovician), Acadian (Devonian), and Hercynian (Carboniferous) tectonic movements (Laboun, 2010).

In South America, several Paleozoic intracontinental sag basins also formed over the Precambrian basement. They initiated in Cambrian to late Ordovician and were filled essentially by siliciclastics with some evaporates and carbonates. Sedimentation was marked by a glacial influence between late Ordovician and Devonian, in function to their paleo-position relative to the South Pole. The Paraná Basin evolved in connection of the Gondwanide orogeny as a foreland basin (Milani and Zalan, 1999).

The subsidence mechanism of these basins and in particular the CB during Paleozoic is not clear. If post-orogenic extension is likely in the peripheral Pan-African Belts for a relatively short time period (e.g. Kipata et al., 2013 for the Lufilian Arc), it cannot be invoked for the central part of the CB for its entire Paleozoic evolution. The seismic profiles show that the Pan-African deformation within the basin remained localized and most part of it remained tectonically undisturbed during the Pan-African time. Rather, a general extensional context probably established after the final Gondwana assembly.

9.3. Congo Basin in the context of Pangea assembly and breakup

The late Devonian – early Carboniferous saw the first stages of the Variscan collision between Gondwana and Laurussia that led to the formation of the Pangea Supercontinent. It affected the northern Gondwana margin by extensive vertical movements in the Sahara and Arabia domains, where Frizon de Lamotte et al. (2013) recognised a late Devonian unconformity associated with tectonic subsidence controlled by extensional deformation and subsequent erosion and peneplanation (“Eo-Variscan” event). The late Devonian - early Carboniferous was a period of major environmental crises with the onset of the Upper

Paleozoic Ice House. It corresponds in Central Africa to the hiatus between the Red Beds (our new Aruwimi Supergroup) and the Karoo Supergroup and, in Southern Africa, between the Cape and the Karoo Supergroups (Catuneanu et al., 2005; Tankard et al., 2009). The tectonic versus climatic origin of the hiatus between the Red Beds and the Karoo in the CB is not clear. However, following Sachse et al. (2012), recycled detrital vitrinite are present in the Lukuga Group (Karoo) in the Dekese well. It must originate from eroded sediments not older than late Devonian (the oldest fossil evidence for angiosperms). This suggests that the Lukuga series were fed by an emerging and eroding area of late Devonian - early Carboniferous sediments.

In the Carboniferous-Permian to early Triassic, the Gondwana domain of Pangea was affected on its southern and western sides by the Gondwanide accretionary orogeny as a consequence of the subduction of the Paleo-Pacific under the Gondwana margin (Cawood, 2005). In South Africa, related tectonism is expressed by the Cape Fold Belt, recently dated at 525 Ma (Blewett & David, P., 2016). Hansma, 2013: 246-279 Ma

At the same time, rifting developed along the Tethys side of Gondwana (Delvaux, 2001), described as the Karoo I rifting period by Frizon de Lamotte et al. (2015), and the Tanzanian craton went through an important period of cooling and denudation (Kazanzu et al., 2016). In the center of Gondwana, the CB accumulated the Karoo Lukuga and Lueki groups. The late Triassic - lower Jurassic hiatus in the CB is coeval with a similar hiatus in Madagascar (Geiger et al., 2004), interpreted by Frizon de Lamotte et al. (2015) as a signature for doming. It was at least partly during this time interval that the late Permian - early Triassic tectonic deformation in the CB occurred, leading to the second widespread unconformity (Basal Jurassic unconformity). This period ends with the Karoo magmatism in Southern Africa and the giant Okavango dyke swarm, precisely dated at 179-180 Ma (Jourdan et al., 2004; Le Gall et al., 2005).

Sedimentation in the CB resumed above the Basal Jurassic unconformity during the late Jurassic (Kimmeridgian), in a lacustrine continental setting (Caillaud et al., 2017). It continued until the Cenomanian (Colin, 1994; Delvaux and Fernandez-Alonso, 2015), after which the late Santonian inversion caused widespread basin inversion in North and Central Africa (Guiraud and Bosworth, 1977).

The Cenozoic history of the CB is recorded in terms of denudation (Sachse et al., 2012), landform development (Guillocheau et al., 2015), neotectonics (Delvaux et al, 2016), and current seismotectonic activity (Delvaux and Barth., 2010), in the frame of the general uplift of Southern Africa Plateau (Braun et al., 2014) and development of the East African rift system (Macgregor, 2015), both resulting from a dynamic topography associated with the African superplume (Nyblade and Robinson, 1994).

9.4 Congo Basin in the context of global climatic fluctuations

The CB Basin recorded well the late Paleozoic Gondwana climatic event, marked by a hiatus after the Red Beds and the overlying Lukuga Group deglacial sequence, well-illustrated in the Dekese well. This was the consequence of its passage through the South Pole in late Devonian. In contrast, the other glacial periods that affected Africa are not well evidenced in the available geological data for the CB. The late Ordovician glacial period was relatively short-lived and affected mainly northern Africa (Ghienne et al., 2007). It might have influenced the source of the lower Red Beds by contributing well rounded and well sorted pebbles to the arkoses of the Inkisi Group (Alvarez et al., 2005).

The Neoproterozoic glacial events (Hoffmann and Li, 2009) have been recognised in the Neoproterozoic belts surrounding the CB. The Kaigas (~750–720 Ma), Sturtian (~715-680) and Marinoan (~660-635 Ma) glacial events were described in the Damara belt on the southern edge of the Congo Craton (Hoffmann et al., 2015). The Sturtian and Marinoan are well known in the West-Congo Belt (Delpomdor et al., 2016) and in the Lufilian Arc in the Katanga Supergroup (Cailteux and de Putter, 2019). The Akwokwo diamictite in the Lindi Supergroup on the northern margin of the CB (Verbeek, 1970) is interpreted as a Sturtian event (Kadima et al., 2011b). The Gilson and Mbandaka deep wells drilled in the CB traversed almost the entire Neoproterozoic sequence, but the observation conditions (drill cuttings of mainly clastic sequences) did not allow recognising the Neoproterozoic glacial sediments.

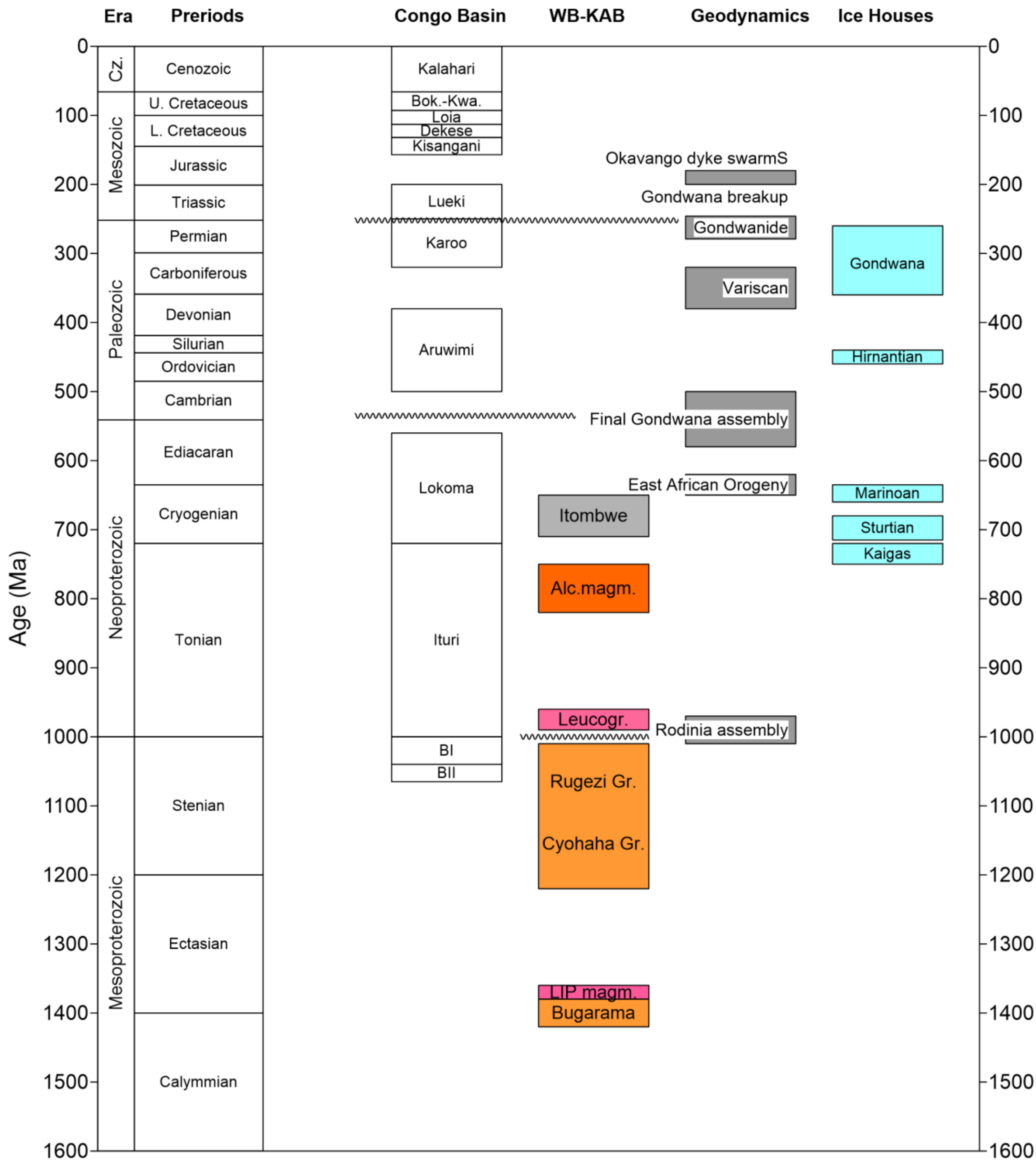


Figure 16: Synthesis of the stratigraphic evolution of the CB in relation with the evolution of the Western Branch of the Karagwe-Ankole belt (WB-KAB), global geodynamic and glacial events.

10. Conclusion

We investigated the formation and evolution of the CB trough analysing all available geological and seismic data. This large data set makes it possible to reconstruct in greater detail than before the stratigraphic and tectonic history of this basin. We reconstructed the spatio-temporal evolution of the CB, integrating it in the evolution of the entire African continent during the last 1 billion years. After a review of the existing knowledge, we proposed a revised seismostratigraphic scheme for the CB, based on our interpretation of the seismic profile and the integration of well and outcrop data. We computed depth maps for the prominent reflectors and thickness maps for the seismostratigraphic units. This allowed us to highlight the three-dimensional evolution of the CB trough time.

The CB is a remarkable intracontinental sag basin, which initiated in the late Mesoproterozoic, most probably as a failed rift basin. It recorded the deposition history of up to one billion years of sediments, one of the longest geological records on earth above a metamorphic basement. It registered several global glacial events in a geodynamic setting, evolving from the end of the Rodina amalgamation to the Gondwana assembly and breakup while drifting over the South Pole and terminating at the Equator. Its early history parallels the evolution of the Mesoproterozoic-Neoproterozoic Kibaride belts of Central Africa. Surrounded by Pan-African orogenic belts in the late Neoproterozoic to Cambrian, it was affected by far-field deformations and associated vertical movements that left a prominent tectonic unconformity coeval with well-expressed Pan-African unconformities elsewhere in Gondwana. During its late Paleozoic to early Mesozoic evolution, sedimentation occurred in the context of the Gondwanide orogeny that occurred along the southern margin of Gondwana. It induced locally intense tectonic reactivation and general vertical movements, leading to the development of a second basin-scale unconformity (Basal Jurassic). The CB might also have been locally influenced by more distal tectonic events, but the current data available do not allow to precise that.

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13 Data sources:

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