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The Upper Jurassic Stanleyville Group of the eastern Congo Basin: An example of perennial lacustrine system

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A B S T R A C T

The intracratonic Congo Basin, located in the Democratic Republic of Congo (DRC), is the largest sedimentary basin of Africa. The Jurassic strata outcrop along its eastern margin, south of Kisangani (formerly Stanleyville). In the last century, the Upper Jurassic Stanleyville Group was described as a lacustrine series containing a thin basal marine limestone designed as the “Lime Fine” beds. Since the proposal of this early model, the depositional environment of the Stanleyville Group, and especially the possible marine incursion, has been debated, but without re-examining the existing cores, outcrop samples and historical fossils from the type location near Kisangani that are available at the Royal Museum for Central Africa (MRAC/KMMA, Tervuren, Belgium). In order to refine the former sedimentology, a series of nine exploration cores drilled in the Kisangani sub-basin have been described. This study aims at integrating sedimentary facies in existing sedimentary models and to discuss the hypothesis of the presence of Kimmeridgian marine deposits along the Congo River near Kisangani, a region which lies in the middle of the African continent. Eight facies have been identified, which permit a reinterpretation of the depositional environment and paleogeography of the Stanleyville Group. The base of the Stanleyville Group is interpreted to represent a conglomeratic fluvial succession, which filled an inherited Triassic paleotopography. Above these conglomerates, a transition to a typically lacustrine system is interpreted, which includes: (1) a basal profundal, sublittoral (brown to dark fine-grained siltstones with microbial carbonates, i.e., the “Lime Fine” beds) and littoral lacustrine series; covered by (2) a sublittoral to profundal interval (brown to dark organic-rich, fine-grained siltstones), which corresponds to the maximum extent of the paleo-lake; and, finally (3) a shallow lacustrine series (greenish calcareous siltstones and sandstones with red siltstones). Unlike what has been proposed, the “Lime Fine” beds are interpreted herein to be of lacustrine origin, rather than representing a Kimmeridgian marine transgression. We conclude that a Jurassic marine transgression did not, in fact, occur in the eastern region of the Congo Basin.

1. Introduction

Near the center of the African continent, the Congo Basin was probably initiated as an aborted rifted basin during the early Neoproterozoic (~1.0–0.9 Ga), and then it evolved into an intracratonic basin in the Phanerozoic (Kadima et al., 2011a). During the Mesozoic, continental conditions prevailed for most of this time; however, some workers have suggested that brief marine incursions during the deposition of the Upper Jurassic Stanleyville Group and Upper Cretaceous Kwango Group may have flooded the basin (Cahen, 1954, 1983). Moreover, due to its large size (about 1.2 million of km^2), the deposition of continental series in the Congo Basin was driven by geological processes other than those governing the deposition of sediments in the surrounding Mesozoic to Tertiary rifts. For instance, a short marine incursion during the Kimmeridgian (~155 Ma) was proposed to have reached the area of Kisangani (former Stanleyville) from the Indian paleo-coast (Cahen, 1983). Indeed, a thin (43 cm thick) marker horizon of limestones, the “Lime Fine” beds (Cahen, 1983), is interpreted as a marine interval in the lacustrine Stanleyville Group. However, the marine origin of this marker horizon has never been questioned or tested (Saint Seine, 1955; Saint Seine et Casier, 1962; Taverne, 1975; Cahen, 1983; Linol et al., 2015a) although it has been widely used as

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evidence for a major marine incursion in the Congo Basin during the Oxfordian-Kimmeridgian (Moore and Scotese, 2012; Scotese, 2014).

This paper re-examines the mode of deposition of the Jurassic Stanleyville Group in the eastern region of the Congo Basin in the Kisangani area along the upper course of the Congo River (locally called as Lualaba). This study is primarily based on a thorough description of a suite of historic sedimentary cores drilled for mining purposes during the first half of the last century and stored at the Royal Museum for Central Africa (MRAC/KMMA, Tervuren, Belgium). Modern facies analysis, a critical review of previous results, sedimentological advances, numerous facies models, and insights gained in the last 50 years in other continental basins allow us to re-examine these cores and to test whether a marine *vs* continental (i.e., lacustrine) depositional model is more appropriate. Specifically, the hypothesis and evidence for a marine incursion during the Kimmeridgian, which have direct implications on many different fields in terms of paleogeography, are re-examined.

2. Geological context

The Congo Basin (Fig. 1), also called the “Cuvette Centrale”, is the largest sedimentary basin in Africa. The current morphology of this intracontinental basin is controlled by the hydrographical system of the Congo River (e.g. Flügel et al., 2015; Guillocheau et al., 2015). It is one of the largest basins in the world, the size of Western Europe and extending over most of the Democratic Republic of Congo (DRC), the southern part of the Republic of Congo (RC), and small areas from Central African Republic (CAR) and Angola. The Congo Basin is surrounded by crustal bulges in the north (Oubanguides) and south (Lufilian Belt and Zambezi Belt) (Burke et al., 2003; Burke and Gunnell, 2008) and by the rift shoulders of the East African Rift System in the east. It is separated from the coastal region in the west by a structural high (West Congo Belt). This bowl shape was probably acquired in the Mid-Cenozoic (Giresse, 2005).

While surrounded by Archean cratonic cores and Paleoproterozoic to Neoproterozoic orogenic belts, its sedimentary sequences are known by scattered and scarce subsurface data (Lepersonne, 1977). Geophysical methods suggest a thickness of Neoproterozoic to Phanerozoic sediments locally reaching up to 9000 m (Lawrence and Makazu, 1988; Daly et al., 1992; Kadima et al., 2011a; Delvaux and Fernandez, 2015). Only four deep boreholes explored at depth the sedimentary infill of the Congo Basin (Fig. 1): two stratigraphic wells drilled by Petrofina for REMINA between 1953 and 1956 (named Samba and Dekese, 2038 and 1856 m deep, respectively), and two exploration wells drilled by Texaco and Exxon between 1981 and 1982 (named Mbandaka and Gilson, 4350 and 4666 m deep, respectively). Correlations with outcrop data gathered along the margin of the basin (Cahen, 1954, 1983; Cahen and Lepersonne, 1978) were used to propose a general stratigraphic scheme of the basin with a succession of three main sedimentary packages, or Megasequences, separated by two major discontinuities: (1) Neoproterozoic to early Paleozoic; (2) Carboniferous to Triassic; and (3) and Jurassic to Cretaceous, overlain by thin Cenozoic deposits (Daly et al., 1992; Kadima et al., 2011a, 2015; Linol, 2013).

The two main discontinuities observed in the Congo Basin were caused by tectonic inversions due to the far-field effects of major tectonic events occurring at the margin of the Congo plate. The first one is confidently related to the Pan-African assemblies of Gondwana, during the Precambrian-Paleozoic transition. The second discontinuity is less well constrained in age, between the top of the Carboniferous-Triassic successions and the base of the Stanleyville Group (Mid-Upper Jurassic), and was named “Base Jurassic Unconformity” by Lawrence and Makazu (1988). From the available geological and geophysical data, it could correspond to the transition between the Permian and the Triassic or to a sedimentary hiatus between the Triassic and the Upper Jurassic. An unconformity has effectively been observed between the summit of the Permian in the Lukuga coal field along the shore of Lake Tanganyika near Kalemie and the Triassic (Cahen and Lepersonne, 1978), but it is not clear whether it is of regional importance. In the Dekese well, the Permian and lower strata are tilted, folded, and faulted, while the overlying beds at the base of which is a thin layer correlated to the Triassic (Linol et al., 2015b) are undeformed (Cahen et al., 1960). In the Karoo Luangwa basin in Zambia, the Triassic (Upper Karoo) overlies the Permian (Lower Karoo) with a slight unconformity, but a major tectonic inversion occurred after the deposition of the Triassic, with up to 2000 m of uplift and erosion (Banks et al., 1955). In Namibia, the Waterberg Thrust exposes basement rocks thrusted over Karoo strata including Triassic and Early Jurassic (Miller, 1983). These discontinuities and associated tectonic deformations can be best explained by far-field stresses related to the distant Gondwanide orogeny at the southern rim of Gondwana during the Permo-Triassic boundary (Daly et al., 1992; Kadima et al., 2011a; Blewett and Phillips, 2016) and possibly also by the early breaking-up of Gondwana and the opening of the Indian Ocean during Triassic to Early Jurassic (Linol et al., 2015a).

3. Literature review of the Stanleyville Group

3.1. Occurrences

The Stanleyville Group unconformably overlies the Haute Lueki (Triassic) and Lukuga (Carboniferous to Permian) Groups and the Neoproterozoic Lindi Supergroup, as well as the Precambrian basement rocks (Cahen et al., 1959; Kadima et al., 2011a), above the early Mesozoic regional unconformity and hiatus discussed earlier. Another (minor) unconformity exists at the top of the Stanleyville Group, separating it from the Loia Group and approximately dated as Neocomian to Aptian on the basis of fossils (Grekoff, 1957; Saint Seine and Casier, 1962; Cahen, 1983).

The Stanleyville Group, commonly attributed to the Kimmeridgian to Barremian-Valanginian (Upper Jurassic-Lower Cretaceous) on the basis of fossils (Cahen, 1983), outcrops in the northeast of the Congo Basin, along the Lualaba River (Congo River, upstream Kisangani), with a thickness of 200–370 m (Passau, 1923; Veatch, 1935; Cahen and Lepersonne, 1954; Cahen, 1983; Delvaux and Fernandez, 2015). It was initially considered to be the lower part (lacustrine facies) of the Mesozoic Lualaba series; (Passau, 1923), however, Veatch (1935) first proposed the name “Stanleyville Beds” for this lacustrine facies. It thins to the south and west of the Congo Basin (Cahen, 1983; Daly et al., 1992) and has also been identified in three of the deep boreholes drilled in the center of the basin. It reaches 332 m in thickness in the Samba well (unit S5, Grekoff, 1957; Cahen et al., 1959) and 108 m in thickness in the Gilson well (unit G5, Colin, 1981). In the Dekese well, 10 m of undated fluvial coarse sandstones are suspected to represent the Stanleyville Group (unit D5 of Linol, 2013; Linol et al., 2015a). The Stanleyville Group is missing in the Mbandaka well, but has been identified in the western part of the basin, in Kinshasa and Brazzaville, filling an irregular top of basement surface, with a maximum of thickness of 20 m preserved (Nicolini and Roger, 1951; Egoroff, 1955; Egoroff and Lombard, 1962; Defrétin-Lefranc, 1967). It was also recognized in boreholes as thin cover over the Kasai craton along the southern side of the Congo Basin (Roberts et al., 2015; Owusu Agyemang et al., 2016).

Cahen (1983) was the first to synthesize all the available data relative to the Stanleyville Group in the Kisangani type area (hereafter referred to as the Kisangani sub-basin). This set of data comes from outcrop studies conducted between the cities of Kisangani and Ubundu and explorations performed by the *Compagnie du Chemin de Fer du Congo Supérieur aux Grands Lacs africains* (CFL) by Horneman and Passau in 1910-13 and 1914-15 (in Passau, 1923); the *Cimenterie du Congo* (CICO) by Mayor in 1953-55; the *Syndicat des Ciments de Stanleyville* (CIMENSTAN) also by Mayor in 1955-56; and the *Minière des Grands Lacs* in 1957-58.

3.2. Lithology

Cahen (1983) divided the Stanleyville Group into 14 stratigraphic horizons (Fig. 2). His descriptions are more detailed for horizons 2 to 10 than for the upper horizons. The Stanleyville Group was deposited over an irregular basement (Passau, 1923), with a maximum estimated composite thickness of 370 m. The depressed areas of this paleotopography are filled by horizons 1, 2, or 3, while horizons 4, 5, or 6 transgress the highs.

The Stanleyville Group is broadly divided into two sub-groups:

The lower part (horizons 1 to 7) comprises a 50-m-thick sequence of green-grey sandy shale/marls, and dark-grey bituminous shale sometimes intercalated with white limestones (the Lime Fine beds of Cahen et al., 1959). This lower part is observed in exploration cores and scattered outcrops along the river banks of the Lualaba and tributaries between Kisangani and Ubundu.

The upper part (horizons 8 to 14) is composed of a sequence of shale, marls, and fine sandstones, purplish red to brownish red. This part is 320 m thick, outcrops around Kisangani, and is also observed in the Samba well (165 m thick).

The transition between the lower and the upper parts is progressive, highlighted by a pebble bed, passing laterally to sandstones (Cahen, 1983).

In the western Congo Basin, the Stanleyville Group, found in a core drilled in Kinshasa (Egoroff and Lombard, 1962) and also in Brazzaville outcrop, is represented by up to 20-m-thick beige, rose, whitish to greenish micaceous shales with calcareous layers rich in fossils (ostracods, phyllopods, and fish debris). The calcareous level (thickness not provided but equivalent to the one of the Lime Fine horizons in Kisangani, Cahen, 1983) was correlated to the Lime Fine horizon described in the Kisangani region on the basis of ostracods and phyllopods paleontology (Egoroff and Lombard, 1962). These carbonates deposited in the western part of the basin were interpreted as continental deposits.

The main characteristics of the Stanleyville Group based on the

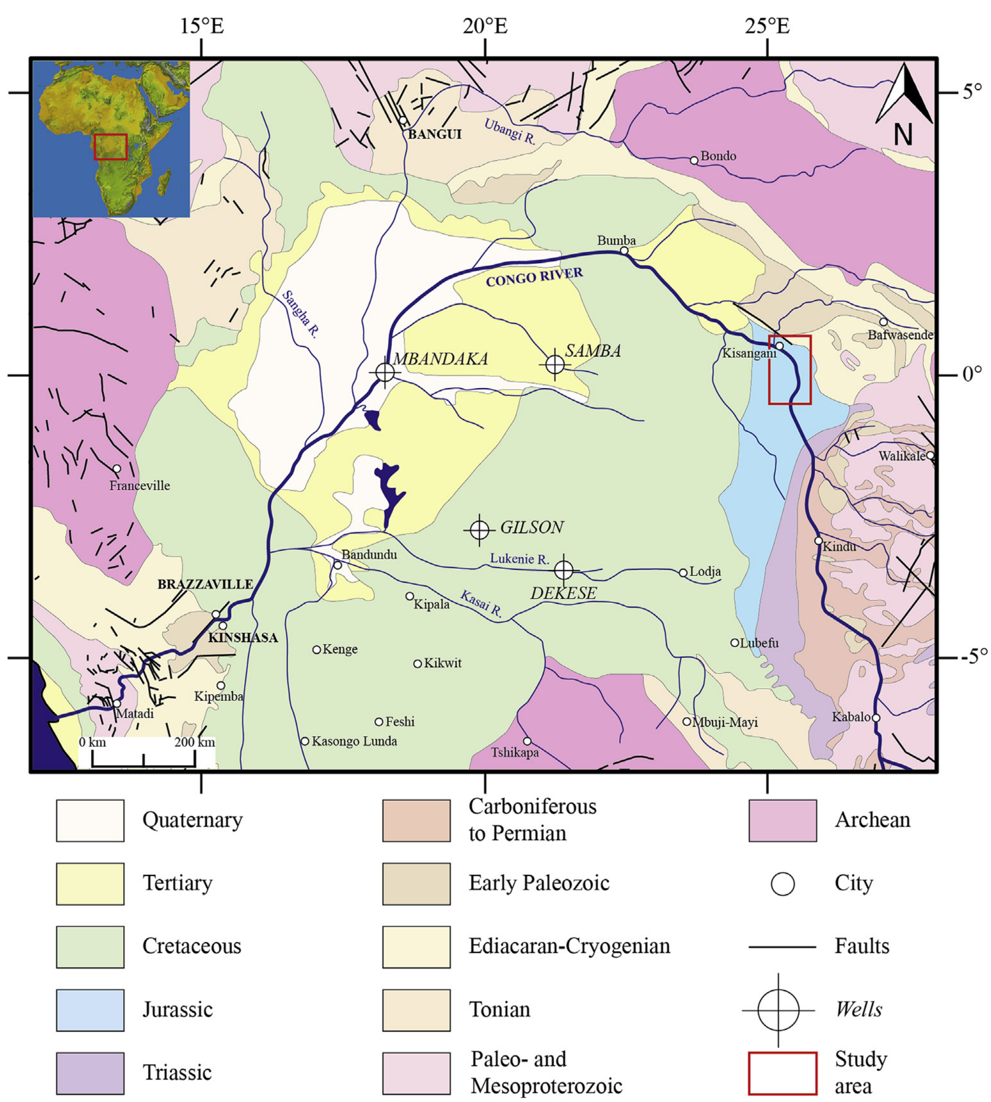

Fig. 1. Geological map of the Congo Basin, after Kadima et al. (2011a) and Linol et al. (2015a).

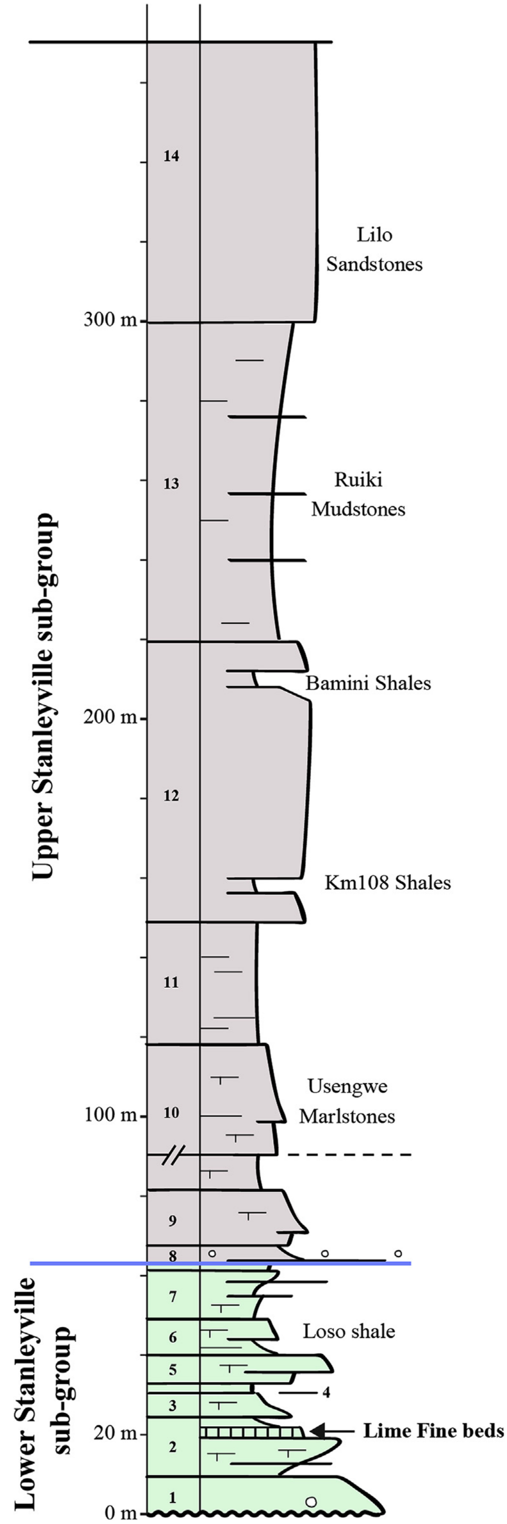

Fig. 2. Lithostratigraphy of the Stanleyville Group (Kimmeridgian to Barremian-Valanginian) in the Kisangani sub-basin as summarized by Linol et al. (2015a) based on an interpretation on Cahen (1983).

early conclusions of Defrétin-Lefranc (1967) are summarized by Cahen (1983) on the basis of geological, chemical, and paleontological data as follows:

The base is made up of conglomerates filling a paleotopography (irregular thickness, often few meters, Cahen, 1983). Above, there are several beds of limestone (horizon 2, better known as Lime Fine beds, 43 cm thick, Fig. 3) thinly interbedded with brown shales. These Lime Fine beds are observed in many wells and have been interpreted as witnessing a brief marine incursion from the east or the northeast (Saint Seine and Casier, 1962).

Sediments overlying the Lime Fine record: (1) quiet phases of sedimentation, and (2): subsidence or weak and distant tectonic phases (Cahen, 1983).

The Stanleyville Group is deposited in a closed or quasi-closed lacustrine environment with brackish waters as demonstrated by the presence of analcime (mineral formed by retention of soda in saline waters, Vernet, 1961 and Vanderstappen and Verbeek, 1964).

An improved stratigraphic interpretation for the Stanleyville Group is proposed by Linol (2013) and Linol et al. (2015a) after redescribing the cored Samba well (Cahen et al., 1960). He delineates two second-order sequences, which he correlates with the lower and upper parts of the Stanleyville Group: (1) a transgressive sequence with basal tidal and flood deposits underlain by soft deformed sands and capped by a black shale unit at the top; and (2) a regressive sequence that begins with fluvial and deltaic deposits with ferricretes and finishes with a surface of emersion and erosion. These sequences form a complete depositional cycle. He interprets this cycle to be related to a phase of extension in the Congo Basin, initiated during the early break-up of Gondwana in the Upper Jurassic. In the drill cores of the Dekese well, Linol et al. (2015a) identified ~300-m-thick aeolian dune deposits, which they correlate with similar but thinner deposits interpreted from cuttings in the Gilson and Mbandaka well. They named this aeolian succession as the Dekese Formation and considered it to be stratigraphically between the Kimmeridgian Stanleyville Group and the Albian Loia Group (Linol et al., 2015a).

3.3. Biostratigraphy

Further information on the age and paleoenvironment of the Stanleyville Group is provided by fossils such as tetrapods, fishes, molluscs, crustaceans, phyllopods, ostracods, and some pollen (Cahen, 1983). The main biostratigraphic assemblages used are fishes, phyllopods, and ostracods. Most of the studies conclude to a Kimmeridgian to Barremian-Valanginian age (Saint Seine, 1955; Grekoff, 1957; Cox, 1960; Saint Seine and Casier, 1962; Pinto and Sanguinetti, 1962; Taverne, 1975; Maheshwari et al., 1977; Lepersonne, 1977; Cahen, 1983; Colin, 2010; pers. com. in Linol, 2013), but others indicate an Aalenian to Oxfordian age (Stough, 1965; Colin, 1994). The initial Kimmeridgian age for the

Fig. 3. Outcrop of Lime Fine beds in the Kisangani sub-basin (photograph provided by D. Delvaux).

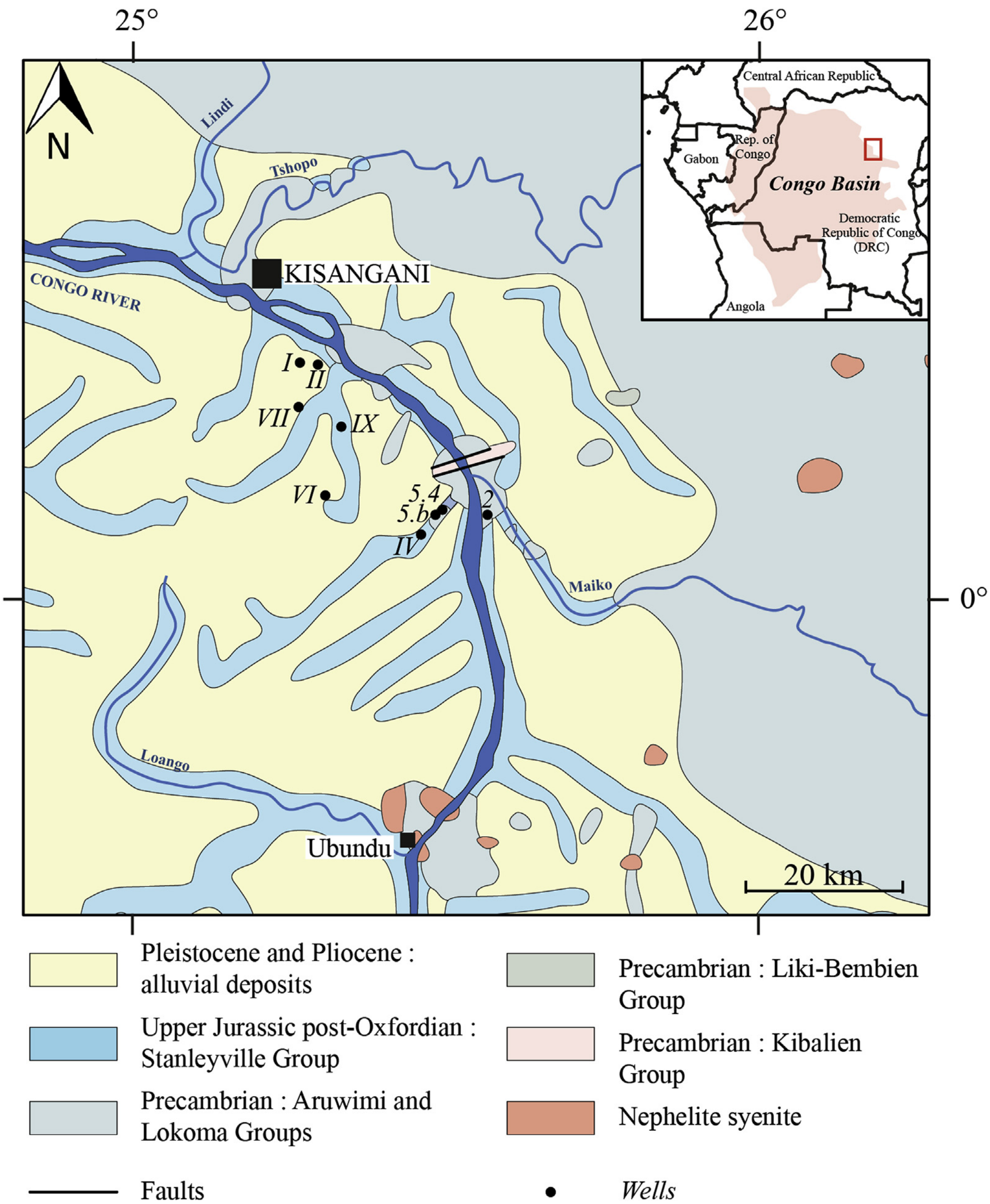

Fig. 4. Location of studied wells in the Kisangani sub-basin.

Stanleyville Group was based on fossil fishes (Saint Seine, 1955). But, after a revision of the fossil fishes, Taverne (1975, pers. comm., 2012) concluded that high endemicity of the fauna in the Stanleyville basin made precise age evaluation difficult. The only two species that have a large repartition (*shark Hybodus* and *amiiform Caturus*) are known during the entire Triassic and Jurassic but are clearly pre-Cretaceous taxa (Taverne, pers. comm., 2012). A precise age determination on the basis of fossil fishes alone is, therefore, not possible.

After a revision of the available palynological and micropaleontological evidence, Colin (1994) proposed a Middle Jurassic (Aalenian-Bathonian) age using correlations with the M'Vone Formation of Gabon and the Aliança Formation of the Reconcavo-Tucano Basin in Brazil. However, Colin (pers. com. in Linol, 2013; Linol et al., 2015a) revised his interpretation and proposed an Upper Jurassic age for the Stanleyville Group.

In this paper, we consider an Upper Jurassic to early Cretaceous age (Kimmeridgian to Barremian-Valanginian) for this Group, which has also been accepted by Giresse (2005), Kadima et al. (2011a, 2011b), Myers et al. (2011), Linol (2013), Delvaux and Fernandez (2015), and Linol et al. (2015a) on the basis of a synthetic publication by Cahen (1983).

3.4. Depositional conditions

The depositional environment of the Stanleyville Group is generally considered as lacustrine to slightly brackish (Cahen, 1983). It was initially considered as the lacustrine facies of the Mesozoic Lualaba series (Passau, 1923; Veatch, 1935; Cahen and Lepersonne, 1954). A limited marine influence was suggested by fishes and pelecypods present in a 43-cm-thick carbonate horizon (Lime-Fine beds, Fig. 3), near the base of the Group (de Saint Seine, 1955; de Saint Seine and Casier, 1962) and by the relative abundance of limestones in that horizon (Cahen, 1983). However, ostracods (Grekoff, 1957) and molluscs (Cox, 1960) indicate fresh water to slightly brackish environment. Colin (1994) also showed that all the ostracods are lacustrine and found no marine microplankton in the palynological preparations. Geochemical and petrographic analysis of the organic matter content in the Stanleyville shales show that they are composed predominantly of algae-derived aquatic organic matter and small amounts of terrestrial higher plant material (Sachse et al., 2012). This suggests a predominantly lacustrine setting.

According to Defrétin-Lefranc (1967), the presence of numerous phyllopods in many horizons is a clear indication of a hot and humid climate with seasonal dry periods. A non-marine origin for the Stanleyville Group is also suggested by the presence of analcime in most of the shales and sandstones, suggesting a lacustrine to lagoonal environment (Vernet, 1961; Vanderstappen and Verbeek, 1964). The two fossil fishes identified in the Stanleyville Group (*squale Hybodus* and *amiiform Caturus*) have a large repartition and are currently known also in continental lacustrine settings (Taverne, 2011a, 2011b, 2011c and Taverne, pers. com.). Their presence in the Stanleyville Group only shows that the paleolake was hydrologically connected to the sea by a river network, allowing some faunal exchange. The argument put forward by Saint Seine (1955) in favor of a short marine incursion is, therefore, debatable, and there is no clear or definitive evidence for a marine influence.

However, Linol (2013) and Linol et al. (2015a) evidenced possible tidal deposits in the basal part of Stanleyville Group (unit S5a) in the Samba well, possibly indicating a marine influence. These deposits are found under black shales, which corresponds to the maximum flooding surface in the complete depositional cycle. These tidal deposits are proposed to correlate with the Lime Fine beds in the Kisangani sub-basin, although both areas are located 400 km away. This new interpretation of possible tidal deposits represents a sedimentological argument in favor of a marine influence. These authors argue the hypothesis of a marine incursion proposed by Cahen (1983) on basis of the fossil fishes identified by Saint Seine and Casier (1962). However, because the fossil fishes argument appears no more decisive, we believe that the discussion on the possible marine environment for the basal part of the Stanleyville Group remains open, in particular because Kimmeridgian and Oxfordian are global sea-level maximum in the Jurassic period (Snedden et Liu, 2010).

Myers et al. (2011) also studied the red deposits corresponding to the upper part of the Stanleyville Group in the Samba well. Based on a thorough geochemical analysis, these sediments are interpreted as deposited during a hot and dry climate with poor and seasonal precipitations, temperatures between 25 °C and 40 °C. These deposits are considered as typical lacustrine facies with substantial salinity.

4. Data and methodology

4.1. Data available

We examined the same 59 exploration cores studied by Cahen (1983) in his synthesis on the Stanleyville Group and drilled between Kisangani and Ubundu, between the railway and the Lualaba. These cores are stored at MRAC/KMMA and made available for this study. Most of these wells are relatively shallow, and only representative parts of the cores are preserved. For the present study, the selection of cores relied on three criteria: (1) a significant penetration (at least 30 m); (2) a sufficient amount of cores preserved; and (3) a good representation of typical rocks of the Stanleyville Group.

Thus, nine exploration cores (hereafter in this paper coded "wells") have been studied: cores I, II, S.VII, S.IX, S.VI, IV, 5b, 5.4, and 2 (Fig. 4). Wells have been relocated on a digital elevation model (Shuttle Radar Topography Mission 3; resolution of 3 arc-seconds) using maps extracted from archived reports (wells I, II, IV, S.VII and S.IX in Passau, 1923 and wells 2, 5.4 and 5.b in Mayor, 1955). Their altitude was determined using the SRTM elevation data. In total, a combined 448.3 m of core were logged in this study.

The quality of cores is highly variable, ranging between well-preserved intact cores to cores containing rock fragments and cuttings, depending upon the original recovery. Moreover, it is important to keep in mind during interpretations that the total thickness of the cores is not always preserved. Thus, for example, in an interval of 120 cm, only 30 cm of core may actually be present. Fortunately, the remaining 30 cm are often representative of the other missing 90 cm (lithology has been described in accompanying core notice, but no detailed core log is available). Moreover, the intervals containing fossils such as phyllopods, ostracods, or fish fragments are mentioned in the core notice.

4.2. Sedimentary facies analysis and facies association

In order to build a sedimentary model for the Stanleyville Group in the Kisangani sub-basin, we described the sediments on the basis of their facies. By facies, we consider all characteristics of one sedimentary unit (Middleton and Hampton, 1973), such as its thickness, composition, granulometry, color, biogenic elements, and sedimentary structures.

We followed three steps to build a sedimentary model: (1) facies determinations; (2) interpretation of sedimentary processes for each facies; and (3) grouping of repeatedly occurring sets of facies into discrete facies associations to obtain a combination of sedimentary processes that can then be interpreted into a depositional environment. We used criteria for characterizing the facies, based on the quality of available cores and with distinctive features of the Stanleyville strata, namely colors of shales and siltstones, sizes of particle, and sedimentary structures. Interpretation of sedimentary facies and facies associations was performed through comparison to published data and through comparison with analogues.

The incomplete preservation of the cores induced important limitation for the classification of facies: (1) the contacts between lithologies were not typically observed; (2) it was rarely possible to describe granulometric variations at small and medium scale; and (3) the core preserved may be not representative of the entire interval studied. In addition, there is a general lack of sedimentary structures, particularly in sandstones. For these reasons, differences between the recognized facies may appear somewhat minor.

4.3. Well correlation

Cahen (1983) subdivided the Group into 14 horizons (Fig. 2) and built his lithostratigraphic model based mainly on the preserved cores of CFL wells VII and IX (Passau, 1923), CIMENSTAN wells I, II, and IV, and outcrop samples and observations. The horizons described by Cahen (1983) do not always correspond with the sedimentary facies determined in this study. For example, in well VII, red mudstones are observed instead of green siltstones and sandstones composing the horizon 5 (Fig. 2, Cahen, 1983). At first order, the horizons defined by Cahen (1983) are correct, but they cannot be utilized to precisely correlate wells. In addition to wells I, II, IV, VII, and XI, the CFL well VI (Passau, 1923) and the CICO wells 2, 5b, and 5.4 (1953) have also been described in this study.

4.4. Types of lake basin after Bohacs et al. (2000).

In this study, we use the concept of "Lake-Basin Type" proposed

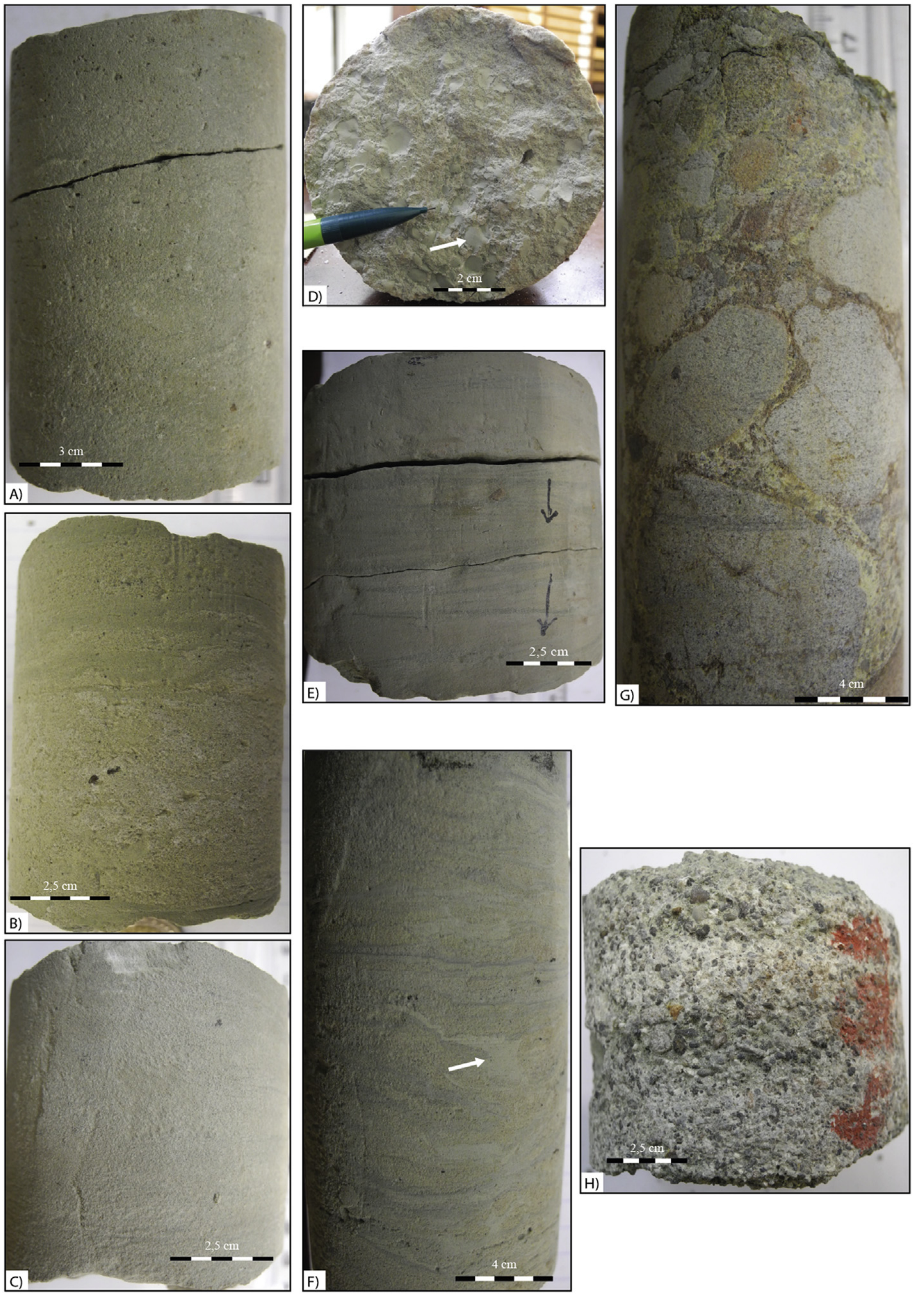

Fig. 5. Coarse-grained lithofacies of the Stanleyville Group (Kimmeridgian to Barremian-Valanginian) in the Kisangani sub-basin. A) Smc facies, massive greenish sandstones. B) Smc facies, with intense bioturbations. C) Sm facies, massive whitish sandstones. D) Sm facies, example of clay balls (white arrow). E) Sr facies, light grey sandstones with greenish argillaceous draping (current ripples). F) Sr facies, oblique and horizontal bioturbations (white arrow). G) C facies, polymict conglomerate that is clast-supported. The matrix is composed of medium sandstones, with cobbles to boulders-sized clasts derived from an ancient basement. H) C facies, sandy conglomerate that is matrix-supported. The matrix is composed of argillaceous sandstones, with pebbles-sized clasts. See Table 1 for detailed descriptions.

by Bohacs et al. (2000). This concept only concerns terrigenous and mixed sedimentation, whereas other lacustrine models exist for lacustrine carbonates (e.g. Platt and Wright, 1991). Lacustrine basins can be of three types: (1) overfilled lake basin with fluvial-lacustrine facies association, (2) balanced filled lake basin with fluctuating profundal facies association, and (3) underfilled lake basin with evaporite facies association. These three types of lake basins are discriminated by sedimentary facies associations, amount of sediments input, open or closed hydrological character of the basin, fossils, organic geochemistry, and geometry of strata. These models are useful to broadly interpret and classify ancient lakes during the course of a preliminary assessment. Moreover, these models allow predicting the distribution of lithologies and organic matter that can be present in such lacustrine basins.

The utilization of these types of lake basin models unfortunately has some limitations. First of all, this classification was developed for the Green River Formation in western United States, and hence, the models are fitted on the lake systems in this formation. They may not necessarily be applicable to other lake basins. Another limitation concerns the representativeness of the sampling or database used to classify the lake basin and, hence, the geographic position of sedimentological studies in the lacustrine system. Sampling bias is frequent, and it is important to keep in mind that these lacustrine models are applicable only for specific areas and

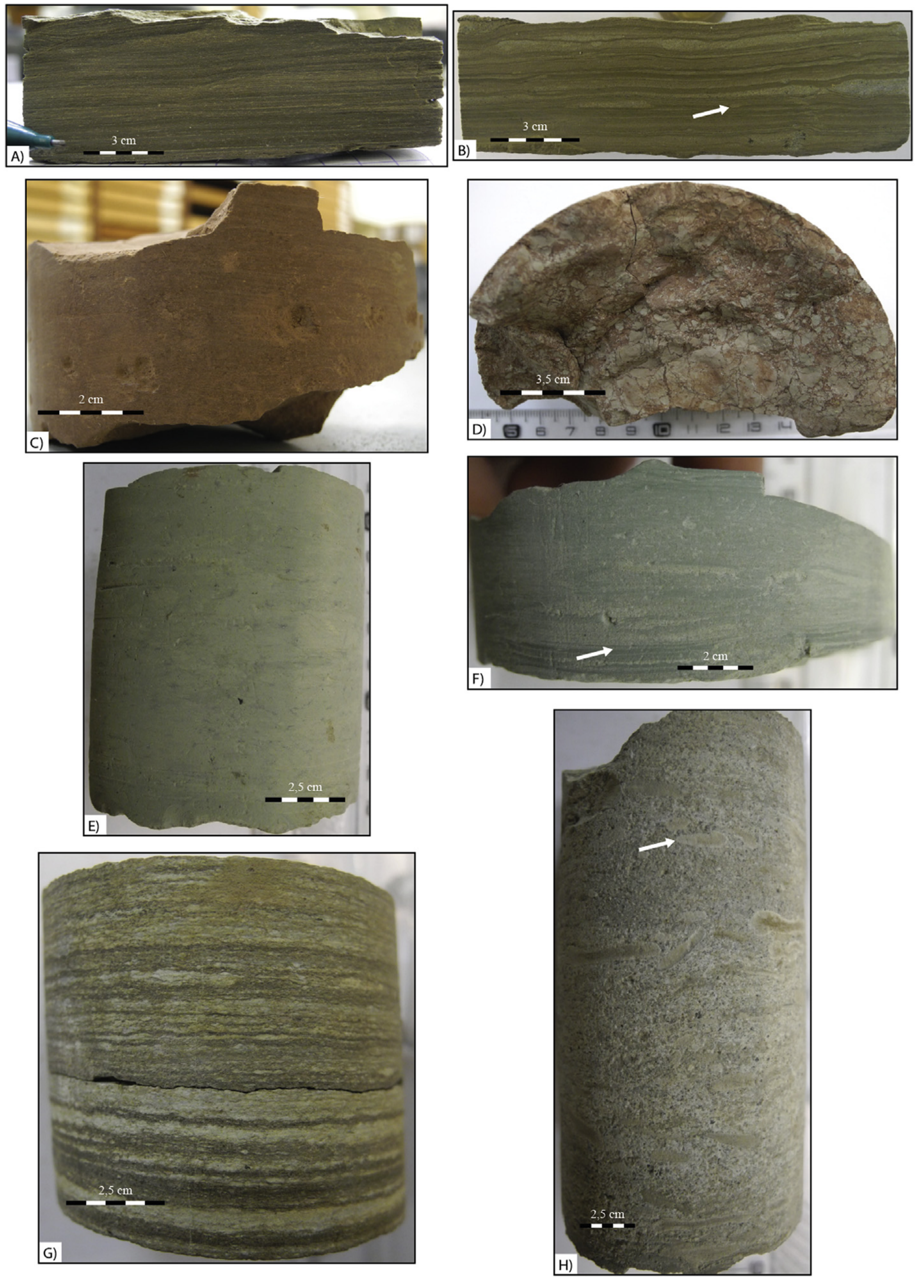

Fig. 6. Fine-grained lithofacies of the Stanleyville Group (Kimmeridgian to Barremian-Valanginian) in the Kisangani sub-basin. A) Fb facies, planar brown to dark shale-siltstones laminae intercalated with light brown shale-siltstones laminae. B) Fb facies, lenticular laminations (lens of fine light sandstones) associated with current ripples and horizontal bioturbations (white arrow). C) Fm facies, massive brownish red to purplish siltstones. D) Fm facies, wholly fractured. E) Fmc facies, massive greenish calcareous siltstones, entirely bioturbated. F) Fmc facies, with sandy planar laminae (white arrow). G) Mc1 sub-facies (Lime Fine beds), planar to undulating fine-grained stromatolites, intercalated with brown siltstones (Fb facies). H) Mc2 sub-facies (Lime Fine beds), reworked stromatolites with well-rounded and elongated casts (white arrow). See Table 1 for detailed facies descriptions.

are not necessarily representative of a whole lacustrine system. Other parameters that need to be taken into account are paleoclimate and tectonics, which may also largely influence lacustrine sedimentation (Renaut and Gierlowski-Kordesch, 2010). Each ancient lake is unique, and, there is not a perfect or valid sedimentary model for all lake basins, especially at the scale of the Congo Basin.

5. Facies descriptions

The detailed sedimentological description of eight facies (Figs. 5 and 6) identified in nine wells is summarized in Table 1. A brief description of facies is presented in this section.

5.1. Conglomerates (C facies)

This facies contains different types of conglomerates (Fig. 5G and H) that are observed in wells I, VII, IX, IV, 5b, 5.4, and 2. Underlying the greenish calcareous sandstones (Smc facies), conglomerates are sited at the base of the wells. Conglomerates are 10 m thick on average (35 cm–61.46 m), but their thickness is very variable from one well to other. The particle size of the matrix (fine to medium sandstones) and of clasts (pebbles to cobbles, rounded to angular) is very variable. Conglomerates are matrix- or clast-supported. There is no fossil or sedimentary structure in this facies. Because there are some different types of conglomerates, several depositional processes are involved (see Table 1).

5.2. Sandstones with ripple cross-laminations (Sr facies)

Sr facies (Fig. 5E) occurs in wells I, IX, VI, IV, 5b, 5.4, and 2, in association with the Smc-Fmc facies and sometimes with the Fb facies. This facies is 219 cm thick on average (35 cm–6 m). It is composed of fine light yellowish to light grey sandstones moderately to well sorted. Greenish argillaceous draping occurs and corresponds to flaser lamination (sometimes wavy lamination) with current ripples. Oblique and horizontal bioturbations (Fig. 5F) are sporadically present, and plant debris are common. This facies occurs in the lower and middle parts of the wells.

5.3. Massive fine-grained (Fm facies)

The massive fine-grained facies (Fig. 6C) occurs in wells I, II, VII, and XI. This facies is 460 cm thick on average (39 cm–18 m). It is often associated with the Fmc-Smc facies. The Fm facies is composed of brownish red to purplish siltstones sometimes calcareous, and the sediment has a lumpy appearance. These sediments are frequently massive, but they can be mottled or fractured with intrusions of greenish siltstones (Fmc facies, Fig. 6D). While fish debris are rare, ostracods and phyllopods are common. These deposits are similar to those described by Myers et al. (2011) in the Samba well, corresponding to the upper part of the Stanleyville Group (Cahen, 1983). In our study, the Fm facies is not present in the lower part of the wells.

5.4. Massive carbonated fine-grained (Fmc facies)

This greenish marls Fmc facies occurs in all wells and has an average thickness of 244 cm (10 cm–11.13 m), and it is distributed homogeneously in all the wells. Greenish marls are often associated with the Smc facies described hereafter and occasionally with the Fm and Fb facies. It is mainly composed of greenish calcareous siltstones tending to marls (Fig. 6E). It has a plastic texture, and frequently calcite is recrystallized into fractures. Sediments are massive, but sometimes planar laminae occur (Fig. 6F). Occasionally, rocks are fractured and filled with red siltstone intrusions. There are sometimes bioturbations, pyrite, and calcite nodules. Moreover, some plant debris have been found. Fossils recorded are fish fragments, phyllopods, and ostracods.

5.5. Massive carbonated sandstones (Smc facies)

The greenish calcareous sandstones Smc facies (Fig. 5A) is 106 cm thick on average (10 cm–405 cm) and is present in all studied wells. It is often associated with greenish marls (Fmc facies) and rarely with the Fb and Fm facies. It corresponds to fine to medium greenish sandstones that are moderately to well sorted. Sandstones are often argillaceous and can be very calcareous. Rounded pebble clasts derived from ancient basement are sometimes identified. Generally, there is no sedimentary structure except rare current and wave ripples. Bioturbations (Fig. 5B) and pyrite are common, and no fossil has been found in this facies. The greenish calcareous sandstones facies Smc is distributed in all the wells, similar as the greenish marls Fmc facies.

5.6. Massive sandstones (Sm facies)

The Sm facies is 167 cm thick on average (23 cm–6.1 m) and occurs in wells I, IX, VI, IV, and 5.4. They are associated with Fb, Fm, Fmc, and C facies. The Sm facies (Fig. 5C) corresponds to fine to medium whitish sandstones that are moderately to well sorted. Sandstones are often calcareous and sometimes contain ostracods and fish fragments. There are no common sedimentary structures, but the sandstones can contain rare clay balls (Fig. 5D) and sediment injections. Dark mineral concentrations are also observed. These sandstones, although rare, are distributed in the lower and upper part of the wells.

5.7. Microbial carbonate (Mc facies, i.e. Lime Fine beds)

The Mc facies (microbial carbonate) is present in wells 2, 5b, 5.4, I, IX, and IV. It is often associated with Fb facies and can be divided into two sub-facies:

Fine-grained stromatolites (Mc1 facies, Fig. 6G). This corresponds to stromatolites intercalated with brown shale-siltstones (similar to the next facies, organic-rich mudstones) in planar to undulating laminae. These stromatolites are laterally linked hemispheroids and contain horizontal bioturbations and pyrite. Occasional quartzite clasts occur (derived from an ancient basement). This facies contains ostracods, phyllopods, and is rich in fish fragments.

Flat pebble conglomerates (Mc2 facies, Fig. 6H). This rare facies is composed of reworked stromatolites with well-rounded and elongated clasts of brown siltstones. Occasional little cracks are also observed.

These two stromatolitic facies correspond to the limestone named Lime Fine beds in the literature. These two facies are 50 cm thick (15 cm–166 cm) and are present in the lower part of some (but not all) wells.

5.8. Black fine-grained (Fb facies)

The Fb facies is present in all the wells, with an average thickness of 165 cm (20 cm–393 cm) in the studied wells. It is frequently associated with the stromatolitic Mc facies and Fmc-Smc facies. Often, it corresponds to brown to dark shale-siltstones laminae intercalated with light brown shale-siltstones laminae (Fig. 6A). Sediments are only terrigenous and sometimes, they may also have a massive structure. Occasional lenticular lamination (fine light sandstones) associated with current ripples are noted (Fig. 6B). Pyrite and both horizontal and vertical bioturbations are often present. Plant debris and light siltstone to sandstone injections are observed as well as fossils such as fish fragments, ostracods and phyllopods. This facies corresponds to the organic-rich oil shale formerly described in the literature as oil shales (Passau, 1923; Veatch, 1935), and it is present in the lower part of the wells.

6. Facies associations and depositional environment interpretation

6.1. Fluvial facies association (C and Sr facies)

Conglomerates (C facies) of the Stanleyville Group correspond to the two lithofacies of Miall (1996): (i) gravel-bed braided with sediment-gravity-flow deposits and (ii) shallow gravel-bed braided. The important diversity of conglomerates can indicate a braided river system that developed at the base of the Stanleyville Group, fed by proximal elements of the basement. This may explain the great variety in the composition and size of particles, matrix, and clasts.

Other fluvial deposits (Sr facies) are occasionally observed within fine sediments. This facies is similar to the Fl facies of Miall (1996), which is characteristic of overbank deposits. The presence

Table 1
Table of facies attributed to fluvial and lacustrine deposits.

Facies associations	Facies (abbreviation)	Lithology	Average thickness	Sedimentary structures and fossils	Associated facies	Depositionnal process	Interpretations
Fluvial edposits	C (Conglomerates)	Matrix (fine to medium calcareous and argillaceous sandstones) or clast-supported (pebbles to cobbles-boulders), rounded to angular clasts, derived from an ancient basement composed either dominantly of fragments of oolithic limestone from the underlying Neoproterozoic Lindian Group, or of basement quartzite known in the vicinity	10 m (0.35 m −61.46 m)	Not observed	Base of the wells, overlying the ancient basement (Triassic sediments or older)	Strong tractive current (Postma, 1990)	Different types of conglomerates: 1) traction carpets driven by stream flow, longitudinal bedforms, lag deposits and sieve deposits (Gh facies, Postma, 1990; Miall, 1996); 2) plastic debris flow, high-strength, viscous (Gmm facies, Miall, 1996); 3) clast-rich debris flow, high-strength (Gci facies, Miall, 1996)
	Sr (Sandstones with ripple cross-laminations)	Fine light grey sandstones moderately to well sorted, with greenish argillaceous draping, frequent plant debris	2.19 m (0.35 m −6 m)	Flaser to wavy laminations, with current ripples, oblique and horizontal bioturbations.	Mainly Smc-Fmc facies, rarely Fb facies	Argillaceous laminae deposition from suspension, sandstones deposition in weak low-flow regime current (Miall, 1996)	Subaquatic environment with low to moderate energy, sporadically stressed environment
Lacustrine plain to proximal deposits	Fm (massive fine-grained)	Lumpy, brownish red to purplish siltstones, sometimes slightly calcareous	4.6 m (0.39 m −18 m)	Massive, sometimes mottled or fractured, traces of root in one core (N°RG 78.874); rare fish debris, common phyllopods and ostracods	Fmc-Smc facies	Lumpy mudstones deposition from flocculation; occasional marmorisation process and/or emersion or hydrofracturation	Subaquatic environment, flocculation probably favoured by saline waters and mud saturation in waters (Retallack, 1988); occasionally subaerial condition, with onset of pedogenic process
Lacustrine littoral deposits	Fmc (massive carbonated fine-grained)	Greenish calcareous siltstones tending to marls, plastic texture, some plant debris and pyrites, frequent calcite recrystallized into fractures or calcite nodules	2.4 m (0.1 m −11.13 m)	Massive, occasional fractures filled by red siltstones (Fm facies), rare sandy planar laminae; occurrence of bioturbations, fish fragments, phyllopods and ostracods.	Mainly Smc facies, rarely Fb and Fm facies	Mudstones deposition from suspension, with rare low-flow-regime current (Miall, 1996); occasional emersion or hydrofracturation	Subaquatic low energy environment, favorable for subaquatic life (some fossils and plants debris); occasionally subaerial conditions
	Smc (massive carbonated sandstones)	Fine to medium greenish sandstones, moderately to well sorted, often argillaceous, can be very calcareous; sometimes rounded pebble clasts, pyrite	1.06 m (0.1 m −4.05 m)	Massive, except rare small current and wave ripples, common intense bioturbations	Mainly Fmc facies, rarely Fb and Fm facies	Sandstones deposition in the lower part of a flow regime and wave reworking (Postma, 1990)	Subaquatic environment, intense bioturbations have probably destroyed most of the sedimentary structures
	Sm (massive sandstones)	Fine to medium whitish sandstones, moderately to well sorted, often calcareous, occasionally dark mineral concentrations	1.67 m (0.23 m −6.1 m)	No common sedimentary structures, but rare clay balls and sediment injections	Fb, Fm, Fmc and C facies	Upper-flow regime (Miall, 1996), with high reworking (clay balls)	High-energy littoral environment
Lacustrine littoral to sublittoral and profundal deposit	Mc (Microbial carbonate)	Corresponds to Lime Fine beds (Cahen, 1983); 2 sub-facies: 1) fine-grained stromatolites (Mc1 sub-facies), stromatolites intercalated with brown shales and siltstones (Fb facies);	50 cm (15 cm −166 cm)	1) Mc1 sub-facies: planar to undulating laminae, horizontal bioturbations, occurence of ostracods, phyllopods, rich in fish	Mainly Fb facies	1) Mc1 sub-facies: alternation of algal mats and terrigenous particles deposited in suspension; 2) Mc2	1) Mc1 sub-facies: probably formed in deeper water, shape of stromatolites suggests an environment where

(*continued on next page*)

Table 1 (*continued*)

Facies associations	Facies (abbreviation)	Lithology	Average thickness	Sedimentary structures and fossils	Associated facies	Depositional process	Interpretations
		occurence of pyrite, occasional quartzite clasts (derived from an ancient basement); 2) flat pebble conglomerates (Mc2 sub-facies), rare, reworked stromatolites with well-rounded and elongated clasts		fragments; laterally linked hemispheroids shape of stromatolites 2) Mc2 sub-facies: dominance of well-rounded and horizontal clasts, occasional reworked little clasts		sub-facies: clasts transported by dense and viscous flow dominated by laminar shear (Myrow et al., 2004)	light and water intensity were low, causing lateral growing of algae in order to capture a maximum of luminosity (Logan et al., 1964; Flügel, 2004; Ozkan et al., 2010; Sarg et al., 2013); 2) Mc2: high energy environment
	Fb (black fine-grained)	Brown to dark shale-siltstones laminae intercalated with ligth brown shale-siltstones laminae, some plant debris and light siltstone to sandsone injections, occurrence of pyrite; organic matter content can reach up to 25% (Sachse et al., 2012), sediments are only terrigenous	165 cm (20 cm –393 cm)	Massive structure to planar laminae, occasional lenticular laminations (lens of fine light sandstones) associated with current ripples, frequent horizontal and vertical bioturbations, rare soft-sedimentary structures; fish fragments, ostracods and phyllopods	Mc facies and Fmc-Smc facies	Mudstones deposition from suspension, lenticular lamination formed in upper-plane-bed to ripple conditions (Hubert and Hyde, 1982)	Subaquatic low energy environment, with occasional turbulent and rapid deceleration of regime (Hubert and Hyde, 1982)

of such fluvial deposit suggests the existence of sporadic outflow flooding the plains of the paleo-lake.

6.2. Lacustrine facies association

6.2.1. Lacustrine plain to proximal littoral deposits (Fm facies)

The Fm facies is interpreted to represent lacustrine plain to proximal littoral deposits. These sediments have been formed along the paleo-lake in very shallow oxygenated waters (as indicated by red color of facies). Fossils (ostracods and fish fragments) indicate a subaquatic environment. The lack of rootlets marks inhospitable conditions for vegetation near the lake shores. Mudstones are mottled (red mudstones passing to green mudstones), suggesting a reduction process occurring in bioturbated structures and in fractures affecting the sediments. Minerals such as palygorskite and analcime described by Myers et al. (2011) indicate a saline environment with a significant evaporation, compatible with a depositional process by flocculation. Some fractures in the Stanleyville Group of the Samba well are filled by greenish siltstones (equivalent to Fmc facies). They have been interpreted as cracks related to paleosoil development during periods of lake plain emersion or drying-up (desiccation cracks, Myers et al., 2011; Linol et al., 2015a), but they might also be interpreted as water escape structures in a hydrofracturation process.

6.2.2. Lacustrine littoral deposits (Fmc, Smc, Sm, and Mc2 facies)

Several lithofacies characterize lacustrine littoral deposits (Table 1). The most frequent is an association of greenish marls (Fmc facies) and calcareous sandstones (Smc facies), corresponding to marsh and pond and exhibiting some similarities with palustrine sediments in lacustrine carbonate systems (Platt and Wright, 1991; Hanneman and Wideman, 2010). These facies indicate a mixed detrital and carbonate sedimentation. Greenish marls (Fmc facies) are bioturbated and include some plant debris characteristic of a marsh environment. Associated calcareous sandstones (Smc facies) indicate low terrigeneous contribution and some river input. Nevertheless, they also suggest poorly drained floodplains. Indeed, the Smc facies is relatively fine-grained and structureless because they have been destroyed possibly by an intense bioturbation in a marsh environment. This association of facies allows to deduce that: (1) calcite veins and nodules are formed during dry periods; (2) this facies has common characteristics with semi-arid palustrine deposits (Hanneman and Wideman, 2010) and a low-energy shallow environment (Melendez et al., 2009; Alonso-Zarza et al., 2009); and (3) like lacustrine plain deposits, greenish marls (Fmc facies) and calcareous sandstones (Smc facies) are occasionally fractured (same hypothesis that lake plain mudstones, i.e., lake plain emersion, drying-up, or hydrofracturation process).

The Sm facies is not often observed in the studied wells. These clean sandstones (Sm facies) can indicate high-energy littoral deposits. Clay balls are probably formed by reworked mud clasts, and dark mineral concentrations are commonly observed on some beaches. This facies possibly corresponds to well-washed beach deposited in lakeshore environment.

The rare Mc2 facies with flat-pebble conglomerates and reworked stromatolites are formed in a shallow and high-energy environment. The presence of little reworked cracks, characteristics of emersion surfaces, indicates a proximal littoral environment. Such deposits are explained by Bohacs et al. (2007), as resulting from a transgressive lag reworking littoral deposits during the early flooding of a lacustrine system.

6.2.3. Lacustrine littoral to sublittoral and profundal deposits (Mc1, Fb facies)

Fine-grained stromatolites are formed in a quiet aquatic environment with low luminosity. For catching a maximum of light, these wavy to planar stromatolites grow more horizontally than vertically in a sublittoral to littoral environment. They are intercalated with organic-rich mudstones (Fb facies) that are sublittoral to profundal deposits (see below paragraph). The origin of fine-grained stromatolites may have many explanations (Renaut and Gierlowski-Kordesch, 2010; Tänavsuu-Milkeviciene and Sarg, 2012 and Sarg et al., 2013): (1) balance conditions between algae growth and terrigenous inputs that are trapped by algal mats; (2) alternation between suitable periods of algae growth and significant terrigenous inputs; and (3) seasonal climatic variations (arid and humid in case of the Stanleyville Group) that induce rapid fluctuations of lake level.

The Fb facies consists of alternating black and brown laminae deposited by suspension. This indicates a low-energy setting. The origin of these rhythmic deposits is probably related to seasonal climatic variations (Yang et al., 2010; Renaut and Gierlowski-Kordesch, 2010) inducing rapid fluctuations of paleo-lake level. Mudstones with lenticular laminations correspond to sudden diluted and low-energy hyperpycnal flows (Mulder et al., 2003; Renaut and Gierlowski-Kordesch, 2010). Because this facies occurs in all the wells, we can conclude that open water circulation characterized this ancient lake during deposition of this facies. These dark mudstones are rich (up to 25%) in organic matter of type I (lacustrine) (Sachse et al., 2012; unpublished Total S.A. reports). Sachse et al. (2012) have proposed a periodic influence of terrestrial organic matter (type III), but samples studied in 2013 (unpublished Total S.A. reports) do not show any terrestrial inputs. However, both analyses concluded that organic matter is derived from significant amount of aquatic algae deposited in anoxic conditions. All these characteristics indicate a sublittoral to profundal environment.

Neither marine sediment nor tidal deposits have been observed in the Kisangani sub-basin.

7. Typical depositional sequence of the Stanleyville Group in the Kisangani region

Based on the presented facies, facies associations, and on the similar lacustrine formation such the Green River Formation occurring in the Piceance Creek and Great Green River basins in western United States (typical parasequence of the Laney Member, see Bohacs et al., 2007; Buatois and Mángano, 2009 and Tänavsuu-Milkeviciene and Sarg, 2012), we propose an ideal depositional sequence composed of three vertically superposed phases (a, b, and c, Fig. 7). This depositional sequence illustrates an ideal succession of the eight facies proposed with the environmental characteristics interpreted for each phase based on our observations and analogues in the literature.

The base of the Stanleyville Group is characterized by a flooding surface (Fig. 7, phase a). During the early flooding, littoral to sublittoral mixed deposits had formed with deposition of fine-grained stromatolites (Mc1 facies, not present in all boreholes and outcrops). During this phase, the paleo-lake had a relatively small extent, was hydrologically open, and was composed of poorly oxygenated freshwater (as in Buatois and Mángano, 2009). Based on the fish fauna, there was likely intermittent fluvial connectivity between the lake and an ocean to have permitted limited faunal exchange (Taverne, pers. comm, 2012). It is known that algal buildups (Mc1 facies) are formed in shallow warm waters (Sarg et al., 2013). Identical fine-grained stromatolites deposits have been described in the Green River Formation (Tänavsuu-Milkeviciene and Sarg, 2012). Occasionally, flat-pebble conglomerates (Mc2 facies) have been deposited during the transgressive lag. The first phase may not always be preserved in the studied wells.

The flooding continued and the paleo-lake has reached its maximum extent (Fig. 7, phase b). The paleo-lake then became stratified with fresh and oxic surface waters and dysoxic bottom waters. The organic-rich mudstones (Fb facies) indicate high rates of clastic sedimentation and a significant amount of algae produced. The lake was still hydrologically open. The low thickness of profundal deposits may suggest that the lake was not very deep (probably not more than 50 m), and/or this period was short. Thus, anoxic conditions took place at low depth. The organic-rich mudstones described in this study are comparable to organic-rich shale (Bohacs et al., 2007) and littoral to sublittoral oil shale (Tänavsuu-Milkeviciene and Sarg, 2012) of the Green River Formation.

The fluvial inputs (water plus sediments) decreased, except during a few sudden floods (Sr facies). The lake area decreased and evaporation became a dominant sedimentary process (Fig. 7, phase c). The composition of water changed, becoming hypersaline and well-oxygenated. On the lake banks, the Fmc-Smc facies and seldom the Sm facies have been deposited. The association of the Fmc-Smc facies can be similar to dolomitic mudflats facies (Bohacs et al., 2007) and littoral to sublittoral siliciclatic facies (Tänavsuu-Milkeviciene and Sarg, 2012) in the Green River Formation. Above littoral sediments, the lake plain mudstones have been deposited (Fm facies). The paleo-lake reached its minimum area, and a portion of the lake was emerged. It was hydrologically closed and evaporation was still strong (saline minerals occur). The lake plain mudstones (Fm facies) seem similar to the lake plain facies (Bohacs et al., 2007) and shoreline mudstone facies (Tänavsuu-Milkeviciene and Sarg, 2012).

At the end of these phases, a new depositional sequence eventually could be started again. This ideal depositional sequence is not directly observed in the case of the Stanleyville Group.

8. Well correlations, evolution, and characteristics of the Kisangani sub-basin

8.1. Stratigraphic cross-section in the Kisangani sub-basin

Wells have been correlated using the principles of sequential stratigraphy and previously defined typical depositional sequences (Fig. 8). However, only lacustrine sediments are correlated, because there is a lack of data (granulometry, texture, and composition) for conglomerates. Different Maximum Flooding Surfaces (MFS), are correlated and one among these corresponds to the more profundal deposits observed in all the wells (Fb facies). This principal MFS is used to flatten the correlated section. In the lower part of lacustrine sediments, four MFS (among them the more profundal one) and possibly a fifth in wells I and S.VI are interpreted. In the upper part, two MFS have been determined in all wells, and they are potentially better recorded in the wells located in the northwestern region (left of Fig. 8).

8.2. Evolution of the Stanleyville Group in the Kisangani sub-basin

The cross-section (Fig. 8) is flattened on the principal MFS of the Stanleyville Group (Fig. 9), and three main depositional *stages* have been defined.

8.2.1. Stage I of the evolution of the Stanleyville Group in the Kisangani sub-basin

Foremost, the topography inherited from Late Triassic to Early Jurassic denudation or no deposits phase was filled by alluvial deposits (Fig. 9). It is difficult to determine accurately the thickness of the conglomerate unit (see Section 6.1) because its contact with the basement is not systematically penetrated. However, a maximum of 61.5 m was found in the studied wells (borehole IX). Once the

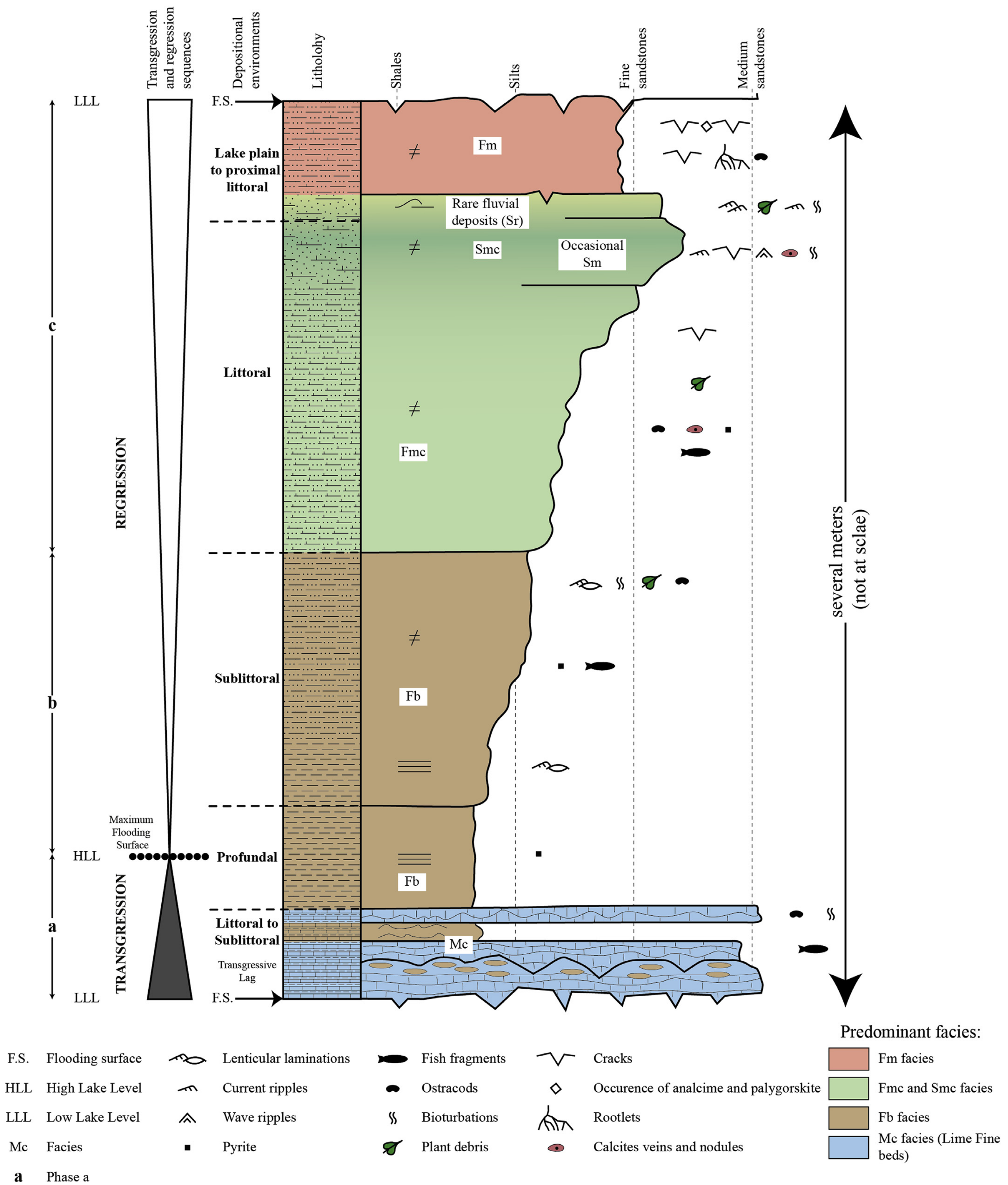

Fig. 7. Typical depositional sequence of the Stanleyville Group (Kimmeridgian to Barremian-Valanginian) in the Kisangani region. Phase a: early flooding in the paleo-lake; phase b: maximum extent of paleo-lake; phase c: paleo-lake area decrease. See text for details.

different types of conglomerates are reported on the location map, it appears that alluvial deposits were more proximal (more heterogeneous and coarsest) in the southeastern wells than in the northwestern wells. This can be an indicator of river inputs that preferably came from the east or southeast in the Kisangani sub-basin. Conglomerates are commonly found at the base of

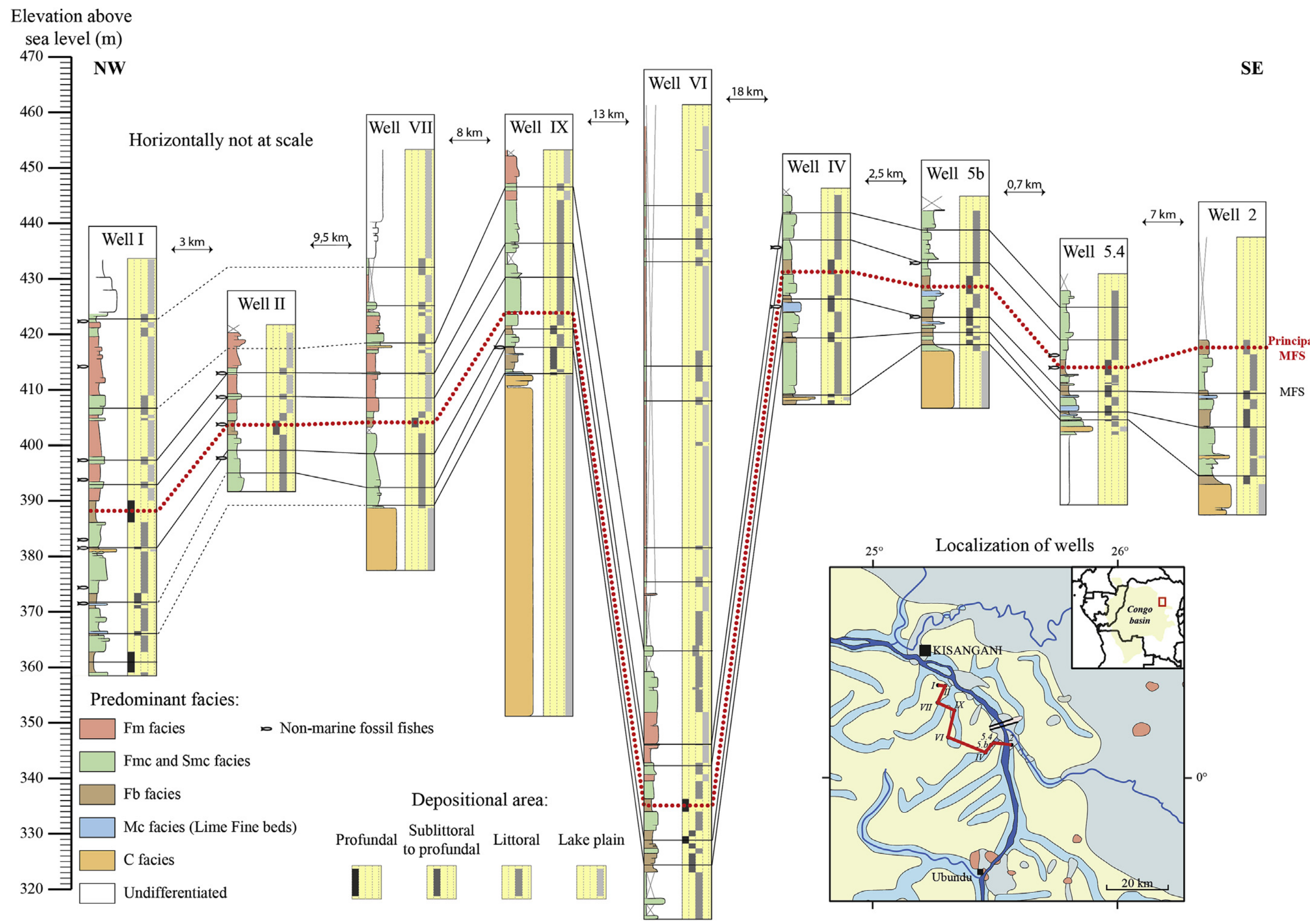

Fig. 8. Well correlation of the Jurassic deposits in the Kisangani region. The principal MFS corresponds to the more profundal deposits observed in all the wells (Fb facies). The fish fragments are mentioned in core notice.

lacustrine sequences as they filled a residual relief. At the end of *stage I*, a slight topography could have remained.

8.2.2. Stage II of the evolution of the Stanleyville Group in the Kisangani sub-basin

Thereafter, the filling of the remaining topography continued, but the sediments have changed to profundal, sublittoral, and littoral lacustrine series. The difference in thickness of wells I and VI has been interpreted as a possible local depression in the topography (Fig. 9). Moreover, it is suggested that well VI was in a more profundal lacustrine environment than the other wells. Firstly, organic matter content is higher in this well (unpublished TOTAL S.A. reports), and this can be explained by a better organic matter preservation with a thicker anoxic water column. Second, there are no stromatolitic beds in well VI unlike in other wells having the Fb facies, which could be the result of a profundal environment preventing the growing of stromatolites. A few stromatolitic beds existed in the northwestern wells, as well as some in the southeast indicating favorable conditions for their development in these two areas (possible paleo-highs). There were two configurations of deposits: (1) low lake levels, when all wells recorded littoral sediments; and (2) high lake levels, when all wells, except two (wells VII and II, probably situated on a shoal), recorded sublittoral to profundal deposits.

This stage ended by the development of the principal MFS over an almost flat topography. Thereby, the transition between *stages II* and *III* corresponds to the principal MFS of the Stanleyville Group (Fig. 9). All wells indicated sublittoral to profundal lacustrine environments, and the lake has reached its maximum extent.

8.2.3. Stage III of the evolution of the Stanleyville Group in the Kisangani sub-basin

Above the principal MFS, the shallow water lacustrine sediments were deposited in a very quiet and flat environment (Fig. 9). This stage was characterized by a lack of sublittoral to profundal lacustrine deposits in the Kisangani region. Similar to *stage II*, there were two configurations of deposits. During low lake levels, a dry area was observed in the northeastern region of the Kisangani sub-basin (wells I, II, VII, and VI), suggesting the lake has reached its minimum extent. Dry areas and littoral zones indicate, like in *stage I*, that river inputs were from the east or the southeast. During high lake levels, all wells recorded a littoral lacustrine environment. However, restricted dry areas could have persisted in some places.

8.3. Depositional model of the Stanleyville Group

Based on a comparison of interpretations presented in this study (facies associations, typical depositional sequences, stratigraphic cross-section and correlations) and literature examples, a depositional model for the Stanleyville Group in the Kisangani sub-basin

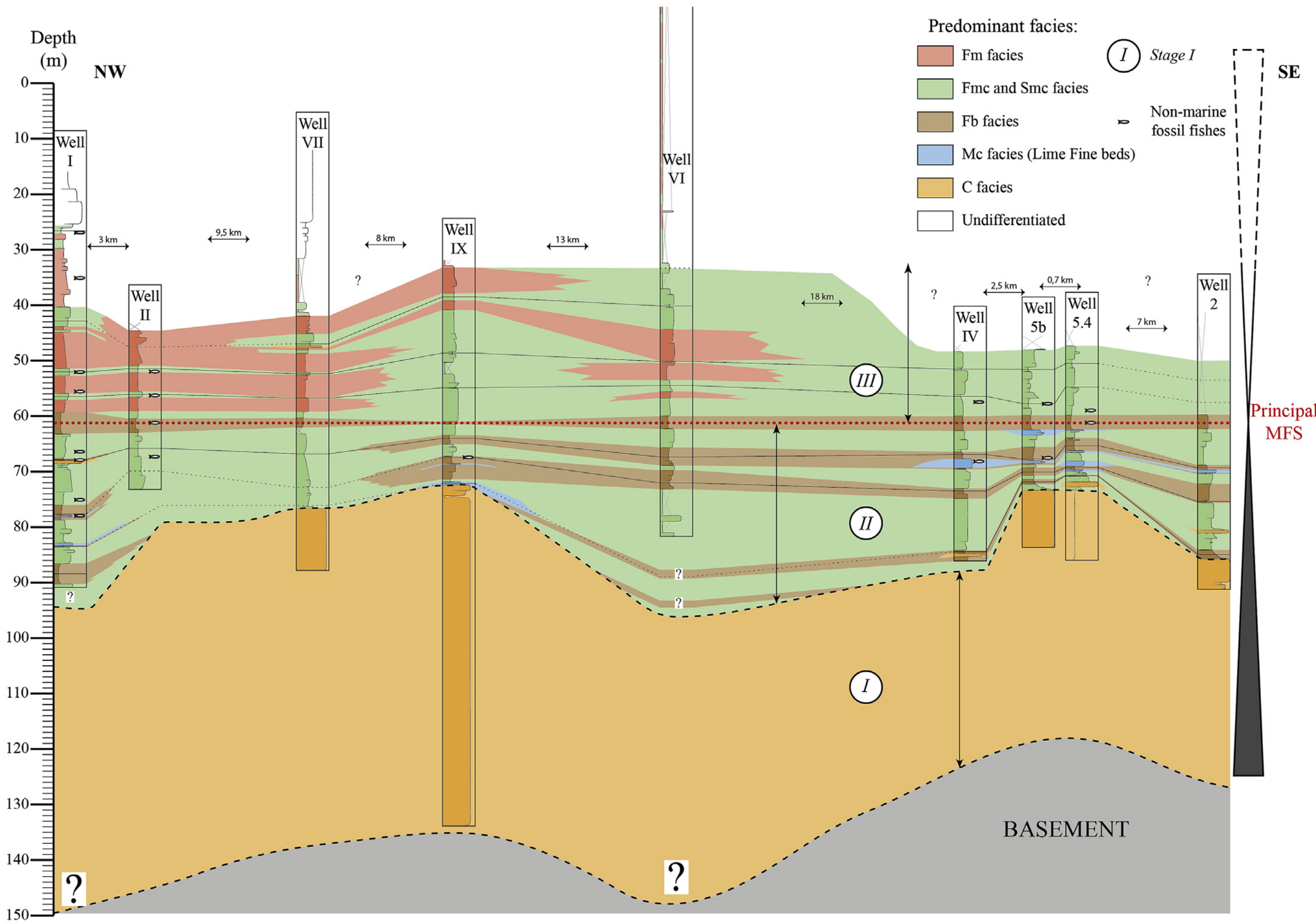

Fig. 9. Stratigraphic cross-section of the Jurassic deposits in the Kisangani sub-basin, flattened at the main MFS. *Stage I*: basal topography filling (alluvial deposits); *stage II*: final topography filling (deep lacustrine deposits); *stage III*: flat topography (shallow lacustrine deposits). The principal MFS corresponds to the more profundal deposits observed in all the wells (Fb facies). The fish fragments are mentioned in core notice.

is proposed (Fig. 10). This model is developed for the Stanleyville Group in the Kisangani-Ubundu area and is not necessarily applicable to the whole Upper Jurassic deposits of the Congo Basin. Deposition of the Stanleyville Group in the Kisangani-Ubundu area occurred on a highly uneven paleotopography inherited from Late Triassic to Early Jurassic, which is a regional discontinuity. It was initially filled by alluvial deposits (*stage I*), before the installation of a lake due to progressive impoundment (*stages II* and *III*).

Two depositional zones coexisted in this perennial lacustrine system (Fig. 10). The first one corresponded to sublittoral to profundal environments, where the sedimentation was detrital and bottom water was poorly oxygenated, favoring organic matter preservation of the periodically algal mats development. The second one corresponded to shallow environments like marshes or ponds where waters were saline and well-oxygenated and sedimentation was essentially chemical with high rates of evaporation. The absence of coarse sediments and of terrestrial organic matter suggests that the lake was weakly supplied in water and sediments and, therefore, that the floodplains must have been poorly drained around the lake.

Two climatic periods are evidenced from this study. During *stage I* and *stage II*, climate was rather humid. Conglomerates of *stage I* are probably characteristic of humid climatic conditions, because they have been deposited in an alluvial system. Deposits of *stage II* also indicate humid climate but with probably dry and humid seasons as indicated by the presence of rhythmic organic-rich mudstones. During this stage, the lake was possibly hydrologically open-filled with freshwater. Contrary, the lake was possibly hydrologically closed during *stage III*, with saline waters. Climatic conditions were probably arid (high evaporation and possible mudcracks). This is consistent with the conclusions of Myers et al. (2011) and Linol et al. (2015a), who proposed, for equivalent deposits in the Samba well (similar to Fm facies), warm and dry climatic conditions with low precipitations, slight seasonal influences, and temperatures between 25 °C and 40 °C.

Lacustrine sedimentation was obviously controlled by climatic variations, but the creation of a sufficient accommodation space must have been caused by tectonic factors that allowed the impoundment of the drainage (Carroll and Bohacs, 1999). The observed rapid and frequent variations of facies and bathymetry are more likely attributed to rapid climatic variations in a general long-term trend toward more dry conditions. Those were probably superposed to a long-term tectonic influence that modified the structure of the existing topography. It could be a localized tectonic subsidence or an uplift that created a drainage sill or both (Kelts, 1988). With all these characteristics, the Stanleyville paleo-lake in the Kisangani-Ubundu region corresponds to the lacustrine model in a “shallow balanced-fill lake basin with low relief margin” of Bohacs et al. (2000). This type of lake basin is controlled by a combination of climatic variations inducing rapid fluctuations of

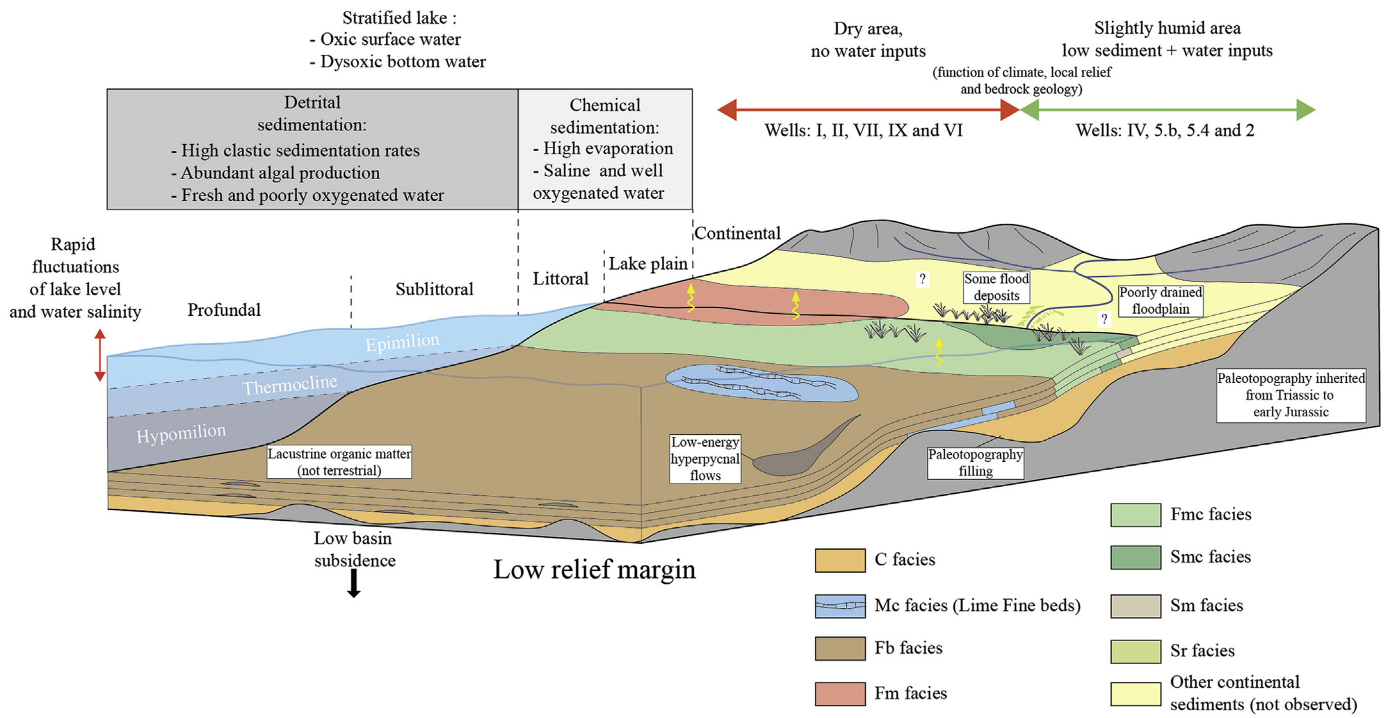

Fig. 10. Depositional model of the Stanleyville Group (Kimmeridgian to Barremian-Valanginian) in the Kisangani area (after Bohacs et al., 2000; Tänavsuu-Milkeviciene and Sarg, 2012). See text for more details.

lake level and tectonic influence, creating the accommodation space (Carroll and Bohacs, 1999). The present Lake Victoria in East Africa is a modern equivalent of such a basin (Bohacs et al., 2000).

9. Discussion

9.1. Marine incursion in the Kisangani region during Kimmeridgian?

The Stanleyville series is commonly described as lacustrine deposits containing some thin beds of marine limestone (Lime Fine beds in literature) in its lower part. The Lime Fine beds have been used as indicative of a marine environment because marine fishes have been described (Saint Seine, 1955; Saint Seine and Casier, 1962; Taverne, 1975). This argument is often used as evidence for a short Kimmeridgian transgression into the interior of the Gondwana supercontinent during the early stage of its dislocation (Cahen, 1983; Giresse, 2005).

As reviewed above, after a recent paleontological revision of fossil fishes from the Lime Fine beds and their worldwide repartition, it appears that the two fish species (*squale Hybodus* and *amiiform Caturus*) from the Stanleyville Group, which have a large repartition and generally found in marine environment, are also observed in other continental deposits (see Taverne, 2011a, 2011b, 2011c for more details, and Tavern, pers. com, 2012). The presence of these fishes only show that the Kisangani sub-basin should have had a connection with the ocean in the early stage of its formation, most probably through a river system. Thus, the fauna arguments cannot be utilized as an absolute marine indicator for the environment of deposition, dismissing the previously interpreted marine environment for the Lime Fine beds.

The Lime Fine beds, interpreted in this study as lacustrine stromatolites, have also been studied geochemically (Rock Eval analysis). Indeed, thin laminae of limestone are interbedded with brown mudstones that are rich in organic matter. Analyses of several samples in the Lime Fine beds (sample n°319 in Sachse et al., 2012) and some samples collected during this study (unpublished TOTAL S.A. reports) have demonstrated that the organic matter is only of type I (lacustrine type), deposited in an anoxic lacustrine environment. We conclude that there is no evidence for a marine incursion in the eastern part of the Congo Basin.

There is, however, a new observation of structures interpreted as tidal deposits by Linol et al. (2015a) in the lower part of the Stanleyville Group in the Samba well (central part of the Congo Basin). As this level is attributed to the Kimmeridgian, it is used as an evidence for marine incursion during the Upper Jurassic. If this interpretation could be confirmed by independent data and taking into account our new interpretation as above, this would indicate a marine incursion reaching the center of the Congo Basin, and not attaining its eastern part.

On the basis of the African topographic model proposed by Doucouré and de Wit (2003) for the Mesozoic period, a brief marine incursion from the proto-Indian Ocean and coming from the northeast Congo Basin is proposed (Cahen, 1983; Giresse, 2005; Doucouré et De Wit, 2003; De Wit, 2007). Due to possible topographic highs remaining around the edges of the Cuvette Centrale, other directions of marine incursion during the Upper Jurassic are not recorded or envisaged.

9.2. Paleogeography of the Congo Basin during the Upper Jurassic

The depositional model of the Stanleyville Group in the Kisangani sub-basin permits a revised look at the paleogeography of the Congo Basin during the Upper Jurassic. At this time, climatic conditions were semi-arid to arid (Myers et al., 2011), and Central Africa was already in subequatorial position. Results of this study coupled with other sedimentological studies (Linol et al., 2015a; Roberts et al., 2015) lead to conclude that:

There were desert conditions in the south of the Congo Basin. Indeed, mixed fluvial, aeolian and ephemeral lake deposits (arid to semi-arid conditions) have recently been observed in the Kasai (Roberts et al., 2015) and Kwango (Linol, 2013) regions, and aeolian sediments have been interpreted in the Dekese and Gilson wells (Linol et al., 2015a).

Fluvial sediments are recorded in the central Congo Basin in the Samba well (Linol et al., 2015a).

In the eastern part of the Congo Basin, where the Stanleyville Group outcrops, lacustrine conditions in seasonal more humid climate are observed with increasing aridity to the top of the Stanleyville Group.

The presence of Jurassic deposits has not been demonstrated in the Mbandaka well located in the central western part of the Congo Basin (Linol et al., 2015a). It is, however, possible that some thin-stacked sandstones may represent this apparent biostratigraphic hiatus.

At the extreme west of the Congo Basin, in Brazzaville (Republic of Congo) and Kinshasa, lacustrine sediments, similar to those presented in this study, have been found at more than 1000 km from Kisangani (Egoroff and Lombard, 1962). It is then possible that another small lake, having similar depositional facies than those identified in the Kisangani sub-basin, was developed simultaneously in the extreme western region of the Congo Basin. Thus, according to Linol et al. (2015a), the southern half of the Congo Basin can be assimilated as a giant "Sahara-like" paleo-desert during the Jurassic. However, the eastern and western part of this giant paleo-desert was probably more humid, because of the presence of perennial lacustrine sediments (Egoroff and Lombard, 1962; Cahen, 1983; this study), while the northern part was a fluvial system (Linol, 2013; Linol et al., 2015a).

According to Stankiewicz and De Wit (2006), the drainage of the basin at this time was southeast directed with a paleo-Congo River flowing toward a proto-Indian Ocean. This output direction lasted at least until the Late Cretaceous according to these authors. In contrast, Owusu Agyemang et al. (2016) showed that during the late Jurassic-Cretaceous, the sediments of the Kasai region at the southern margin of the Congo Basin were sourced from an emerging basement south of the basin, and a large fluvial drainage system must have developed across Central Africa. This large fluvial drainage system was flowing northwards across the basin and merging possibly with another large system from the eastern part of the Congo Basin (Owusu Agyemang et al., 2016). This is consistent with the findings of Roberts et al. (2012), who demonstrated that drainage during the mid-Cretaceous was northwestern-directed, controlled by a northwestern-trending Cretaceous rift that reactivated the Ubendian belt, as shown by current directions in the Cretaceous deposits of the Rukwa Rift Basin and along the northwestern margin of Lake Malawi (unpublished observation of D. Delvaux). Drainage of the Rukwa Rift Basin was later reverted and flew toward the Indian Ocean in Early Paleogene (Roberts et al., 2010). Thus, the drainage of the Congo Basin during the Late Jurassic and the Early Cretaceous remains a topic of debate. In the Kisangani region, the top of the lacustrine sediments reveals an important evaporation phase and lacustrine saline waters (*stage III*), which could indicate a basin hydrologically closed. It is, therefore, possible that the top of the Stanleyville Group was deposited in endorheic conditions during the Late Jurassic.

10. Conclusion

This study, based on an invaluable database, permits to propose a new model for the deposition of the lacustrine series of the Stanleyville Group in the Kisangani sub-basin. The utilization of a thorough sedimentary analysis subdivides the Stanleyville Group deposits into a series of eight sedimentary facies. The facies associations have been interpreted as different depositional environments: fluvial deposits (conglomerates and sandstones with ripple cross-laminations), lacustrine plain to profundal deposits (red massive siltstones), lacustrine littoral deposits (greenish massive carbonated siltstones and sandstones, and whitish massive sandstones), and lacustrine littoral to sublittoral and profundal deposits (microbial carbonates, i.e. the Lime Fine beds, and dark organic-rich mudstones).

The vertical superposition of the facies permits to subdivide the period of deposition into three *stages*: a basal topography filling stage characterized by the deposition of alluvial sediments (*stage I*); a final topography filling stage characterized by the deposition of deep lacustrine sediments (*stage II*); and a flat topography stage characterized by the deposition of shallow lacustrine sediments (*stage III*). The lacustrine *stages II* and *III* are similar to the model proposed by Bohacs et al. (2000) for the fluctuating-profundal facies association in a balanced-fill lake basin. This evolution was likely controlled by a combination of climatic and tectonic factors.

The present study combines a recent reinterpretation of the inferred marine environment from fossil fishes made by Taverne (2011a, 2011b, 2011c), with the proposed attribution of the Lime Fine beds to stromatolitic lacustrine sediments (Mc facies) and the geochemical results (Sachse et al., 2012; unpublished Total S.A. reports) refuting a marine influence in the Stanleyville Group in the area of Kisangani during Kimmeridgian transgression.

In the case of vast basins such as the Congo Basin with a weak control on paleotopography, on surrounding paleoreliefs, on route locations by which marine incursion could have reached this basin, it is reasonable to find a great variability in the depositional environment, and a unique depositional model cannot explain all of the observed variations.

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