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Structure and geological history of the Congo Basin: an integrated interpretation of gravity, magnetic and reflection seismic data

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ABSTRACT

The stratigraphic, paleogeographic and tectonic evolution of the intracratonic Congo Basin in Central Africa has been revised on the basis of an integrated interpretation of gravity, magnetic and reflection seismic data, together with a literature review of papers sometimes old and difficult to access, map compilation and partial reexamination of outcrop and core samples stored in the Royal Museum for Central Africa (RMCA). The Congo Basin has a long and complex evolution starting in the Neoproterozoic and governed by the interplay of tectonic and climatic factors, in a variety of depositional environments. This multidisciplinary study involving 2D gravity and magnetic modeling as additional constraints for the interpretation of seismic profiles appears to be a powerful tool to investigate sedimentary basins where seismic data alone may be difficult to interpret. The tectonic deformations detected in the Congo Basin after the 1970–1984 hydrocarbon exploration campaign in the Democratic Republic of Congo (DRC) have been attributed to crustal contraction and basement uplift at the center of the basin, following a transpressional inversion of earlier graben structures. Two-dimensional gravity and magnetic models run along key seismic lines suggest the presence of evaporite sequences in some of the deeper units of the stratigraphic succession, in the lateral continuity with those observed in the Mbandaka and Gilson exploration wells. The poorly defined seismic facies that led to the previous basement uplift interpretation of the crystalline basement is shown to correspond to salt-rich formations that have been tectonically de-stabilized. These features may be related to vertical salt-tectonics connected to the near/far-field effects of the late Pan-African and the Permo-Triassic compressive tectonic events that affected this African part of Gondwana.

INTRODUCTION

Cuvette Centrale (Central Basin), Cuvette Congolaise, Zaire Interior Basin and Congo Basin are all terms used in the literature to denominate the broad and long-lived intracratonic depression of Central Africa where sediment accumulation, tectonic inversion and erosion occurred in a long history since the Neoproterozoic. This basin is located in the centre of the African Plate, covering most of the Democratic Republic of Congo (DRC, formerly Zaire), the People's Republic of Congo and the Central African Republic (Veatch, 1935; Cahen, 1954; Lepersonne, 1977; Daly *et al*., 1992; Giresse, 2005).

The major problem in depicting the geological history of this broad structure is that outcrops, wells and seismic lines provide a picture too scattered and with a poorly defined time frame to interpret the past geological history of this huge area as that of a single and coherent basin. Depending on the location and time of deposition, the Neoproterozoic–Early Phanerozoic sediments might be related to failed rift basin, foreland basins, or platform cover as in the Taoudeni basin over the West African Craton or the Riphean-Vendian over the Siberian Platform. Since the Late Carboniferous and up to the Triassic, they are mainly related to the Karoo period in the Gondwana continent, with glaciations, rifting and tectonic inversions (de Wit & Ransome, 1992; Burke *et al*., 2003; Catuneanu *et al*., 2005). During the Cretaceous and Cenozoic, a succession of continental deposits separated by peneplanation surfaces and totaling a maximum thickness of 1000 m emplaced in a slow subsidence process (Giresse, 2005). Since the Cenozoic, the basin acquired the form of an internal sag basin, from which the term 'Cuvette Centrale' has been derived by the first explorers. It defines the hydrographic basin of the Congo River and is surrounded by topographic highs interpreted as swells (Burke *et al*., 2003; Burke & Gunnell,

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2008); successively the Adamlia, Nil-Congo, East African, North-Zambian, Bie and Mayombe swells (Fig. 1). Other sag basins also appeared during the same period more to the south (Kalahari and Okavango basins; Haddon & McCarthy, 2005). During the Miocene, broad flank uplift of the Atlantic rifted margin closed the basin, stimulating the formation of gorges and rapids across the Mayombe Mountains and maintaining the basin floor to a present-day altitude of 290 m asl (Séranne & Anka, 2005).

The two most widely used terms to depict this broad, long-lived and multievent intracratonic sedimentary depression are 'Congo Basin' and 'Cuvette centrale'. Both terms appeared almost simultaneously. As reviewed by Cornet (1894), A. Wauters recognized in 1885 that the Congo River and its tributaries were forming an hydrological basin in the form of a large 'cuve' (bowl) with his central part systematically lower in altitude than its periphery. This geographic approach was confirmed by E. Dupont in 1888 (Dupont, 1889), which first specified its geological significance. Cornet (1894) defined the 'Congo Basin' as a geological entity corresponding to all the nonmetamorphic sedimentary formations overlying the crystalline basement, differentiating it from the hydrological basin. He rapidly recognized its possible petroleum potential (Cornet, 1911). The term Congo Basin became internationally used since the memoir of Veatch (1935). In parallel, 'Cuvette centrale', which refer to the present-day bowl shaped depression, became equally used (Evrard, 1957; Chorowicz *et al.*, 1990; Daly *et al.*, 1991, 1992). The geological significance of these terms also varied with time. They were initially defined before the development of the plate tectonic concepts and the present understanding of the dynamics of sedimentary basin formation. While Cornet (1894, 1911) considered all the sediments covering the crystalline basement as part of the basin, only the Phanerozoic (Carboniferous to Recent) sediments were attributed to the basin by Veatch (1935), Cahen (1954) and Lepersonne (1974a, 1974b, 1977). These authors attributed the Neoproterozoic to early Paleozoic sediments overlying the crystalline basement as part of the platform cover. Integrating the plate tectonic concepts, Chorowicz *et al.* (1990) and Daly *et al.* (1991, 1992) reincorporated the pre-Phanerozoic sedimentary succession into the Congo Basin concept. As it is outside the scope of this work to revise these terms and definitions, we will preferably use 'Congo Basin', referring to the entire sedimentary succession above the crystalline basement but without the particular morphological meaning associated to the term 'Cuvette centrale'.

Owing to a scarcity of exposure, the geology of the Congo Basin is poorly known. Although the Congo Basin is a continent-scale feature (1.2 M km^2, i.e. 10% of the area of the Africa continent), recent reviews on sedimentary basins in Africa have sometimes totally ignored it (Selley, 1997) or have restricted their focus on its recent history since the Late Carboniferous times (Lepersonne, 1977) or even the Mesozoic times (Giresse, 2005).

The first exploration work of the Congo Basin combined surface mapping, geophysical surveys and drilling by the 'Syndicat pour l'étude géologique et minière de la Cuvette congolaise' for defining its stratigraphy and structure. In 1952–1956, the 'Société de Recherche Minière en Afrique' (REMINA) drilled two *c.* 2000 m deep stratigraphic wells, fully cored (Samba and Dekese; Fig. 2). The cores are preserved in the Royal Museum for Central Africa, Tervuren, Belgium, constituting a unique geologic data base. The results of this comprehensive exploratory work have been published among others in Cahen *et al.* (1959, 1960) and Evrard (1957, 1960). The seismic refraction and reflection results, calibrated with the Samba and Dekese wells and correlated to outcrop data allowed to sketch the geological structure of the basin (Evrard, 1960). The results confirm the earlier subdivision of the basin stratigraphy in three major sediment packages, a Mesozoic to Recent cover with a maximum thickness of 1200 m, Late Carboniferous to Permian sediments with an apparent thickness reaching 1000 m in the Dekese well (not corrected for the average 40° tilting and the numerous slip planes observed on the core), and earlier sediments several thousands of meter thick.

From 1970 to 1984, a second phase of oil exploration conducted by SHELL, TEXACO and the Japan National Oil Company (JNOC) led to the acquisition of additional aeromagnetic, gravity data and 2900 km of seismic reflection profiles, and geochemical samples (JNOC, 1984). These campaigns were followed by the drilling of two *c.* 4500 m deep exploration wells (Mbandaka and Gilson) by ESSO Zaire. A first compilation of the available data was conducted by Exploration Consultant Limited (ECL, 1988) and the resulting interpretation of the basin evolution was outlined by Lawrence & Makazu (1988). The average thickness of the sediments above the crystalline basement in the central part of the basin is now estimated at 5–6 km, locally reaching 8–9 km. The tectonic evolution model was refined by Daly *et al.* (1991, 1992) who suggested that the basin was initiated in a failed rift setting and that the tectonic features observed on the available seismic lines are related to the Early and Late Paleozoic–Early Mesozoic compressional events, reactivating the rift structures. They proposed that the observed geometries can be explained by a process involving contraction and uprising of the lithospheric crust as far-field effects of the Cape folding event in South Africa. The stratigraphy, structure and petroleum potential of the Congo Basin have been recently reviewed by Kadima (2007).

The structure of the Congo Basin has been interpreted by ECL (1988), Lawrence & Makazu (1988), and Daly *et al.* (1992) as a series of sub-basins separated by basement highs (Fig. 2). In the center of the basin, the narrow WNW–ESE presumed Kiri high is shown to be connected to the broad Lokonia High. Following our integrated interpretation of gravity, magnetic and reflection seismic data, we will present an alternative interpretation with the presumed crystalline basement of the Kiri High is instead composed of salt-rich sediments.

After an updated description of the geological setting (including the well data) and a review of tectono-

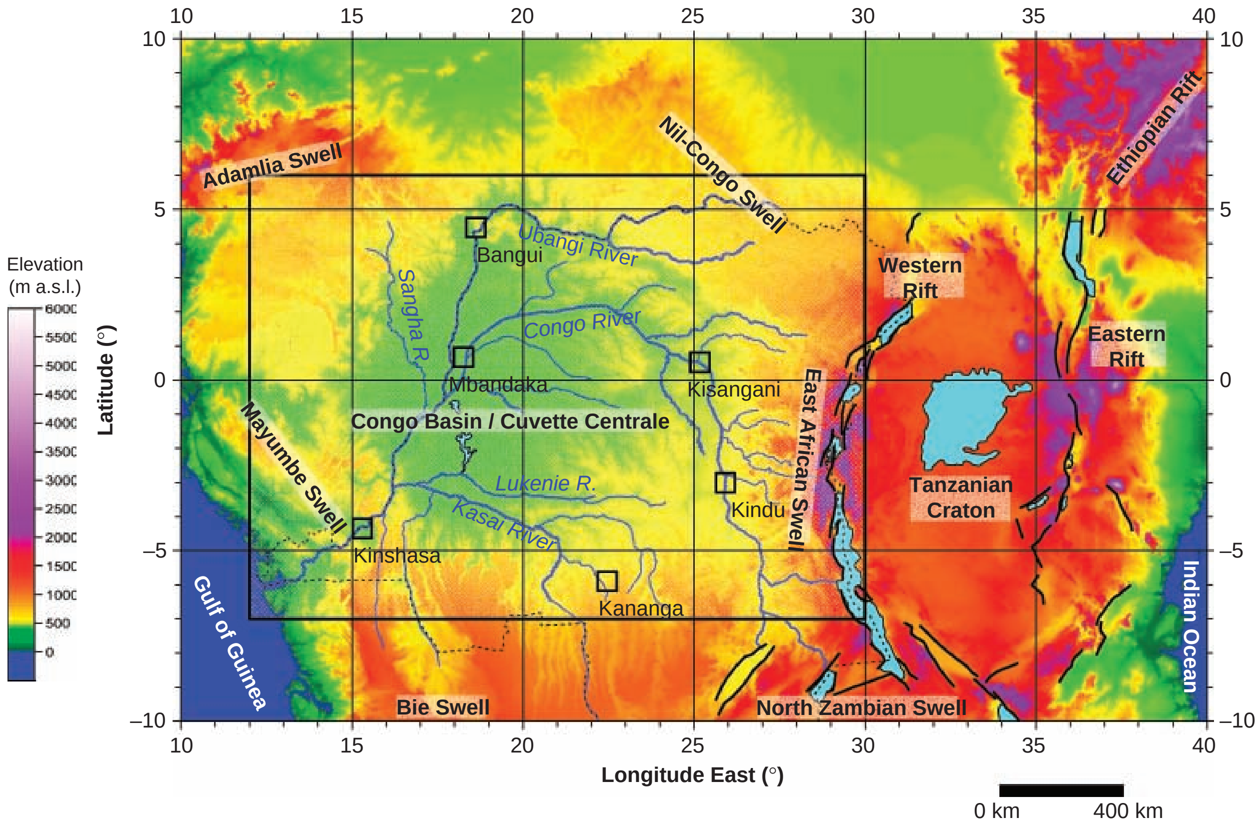


Fig. 1. Oro-hydrography of the Congo Basin in Central Africa. It forms a huge sub-circular depression encircled by relatively high relief zones and drained by the Congo River and his tributaries (Gtopo altimetric data color-coded in function of elevation). Location of the major cities are indicated. Rectangle shows the area covered by Fig. 2.

stratigraphic constraints, this paper proposes a new interpretation of the structure and deformations of the Congo Basin using a multidisciplinary approach integrating well, outcrop and geophysical data with modeling results in order to clarify the structure and deformations of the Congo Basin.

GEOLOGICAL SETTING

The Congo Basin covers about 1.2×10^6 km^2 and is one of the largest intracratonic basins in the world. It is underlain by a thick (200 ± 30 km) lithosphere and coincides with a region of pronounced long-wavelength gravity anomaly (Crosby *et al*., 2010). Cenozoic to Recent sediments occupy the center of the basin while the larger part of it contains Mesozoic sediments. The Paleozoic and Neoproterozoic sediments outcrop at the periphery of the basin and have been explored by drilling in the central part (Fig. 2). They overly a metamorphic to crystalline basement that was initially considered as forming a large cratonic mass: the Congo craton (Cahen, 1963, 1982). Continental-scale tomography however indicates no pronounced lithospheric keel under the central part of the basin, in contrast with thick lithosphere beneath the exposed Archean surrounding blocks (Pasyanos & Nyblade, 2007). The Congo craton is now considered as composed of several Archean nuclei (Angola-Kasai, NE Congo, Chailu/Gabon, Bangweulu) that are welded together as a result of Paleoproterozoic collision orogeny (De Waele *et al*., 2008; Kanda Nkula *et al*., 2009). The presence of tectonic dislocations affecting the sediments of the Congo Basin (Daly *et al*., 1991, 1992; this paper) and its current seismic activity (Ayele, 2002; Delvaux & Barth, 2010) show that the crystalline basement does not behave fully as a rigid cratonic mass.

The Congo basin appears to evolve in a succession of different geodynamic processes, rather than under a single process operating continuously over 800 Ma. Initiation of the basin in the Neoproterozoic could be at least partly caused by intracratonic extension, and the subsequent long evolution is likely influenced by subsidence related to the cooling of stretched lithosphere, despite several periods of basin inversion. Seismic high shear-velocity structures that extend to 250 km depth have been noted beneath the Congo craton (Ritsema & van Heijst, 2000). The GRACE satellite free-air gravity field (Adam, 2002; Crosby *et al*., 2010) shows a spectacular long-wavelength low of − 30 mGal over most of the Congo Basin and − 40 mGal in its center, confirming the existence of a large low-density sedimentary infill, at least partly compensated by high-density material in the lower crust and/or upper mantle but which, according to Braitenberg & Ebbing (2009) cannot be explained fully by a crustal thinning

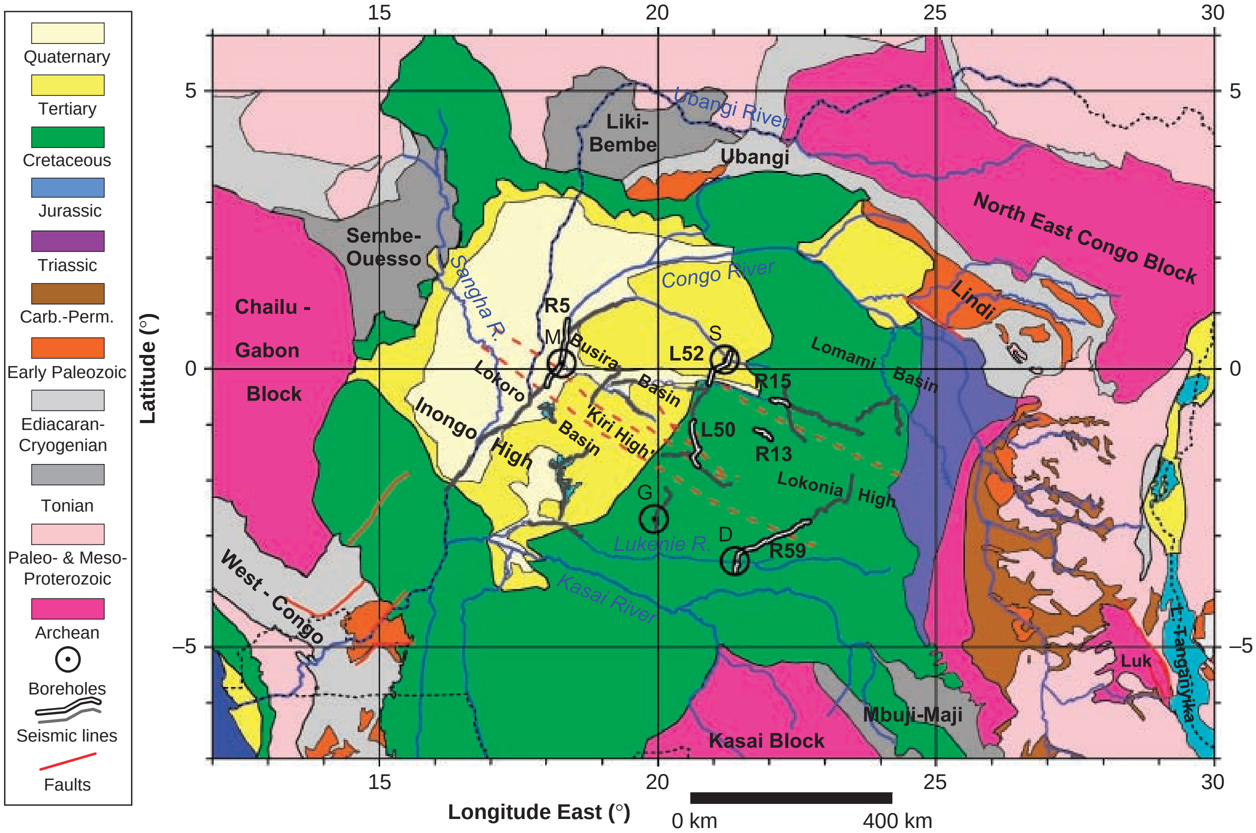


Fig. 2. Simplified geological map of the Congo Basin, compiled from various published map. The stratigraphic units have been assembled into major sequences (Late Neoproterozoic, Paleozoic and Cenozoic), corresponding respectively to seismic units A, B and C as defined here from the seismic and well data. Bold labels define the Archean cratonic blocs, the stratigraphic Groups and the internal structural element of the Congo Basin. Deep faults interpreted from the seismic profiles are shown as dashed lines. Faults that have evidence for activity during the Paleozoic-Mesozoic are shown as continuous lines. Location of the 4 wells: (S: Samba – TD at 2038 m, D: Dekese – TD at 1826 m, M: Mbandaka – TD at 4350 m, G: Gilson – TD at 4536 m), and the seismic profiles acquired between 1970 and 1984 by Shell, Texaco and JNOC. Major morphotectonic provinces are indicated. Luk: Lukuga coal-bearing basin.

mechanism and therefore as due to concealed rift basins. Considering the coincidence of the anomalous topographic depression of the Congo Basin with this large negative free-air gravity anomaly and a large positive upper-mantle shear-wave velocity anomaly, Downey & Gurnis (2009) explain this huge Cenozoic depression by the action of a downward dynamic force on the lithosphere that they relate to a high-density object within the lithosphere. Others relate the observed present-day gravity anomaly to a late phase of basin subsidence in response to a downwelling mantle plume (Hartley & Allen, 1994; Forte *et al.*, 2010). Both Downey & Gurnis (2009) and Crosby *et al.* (2010) place the source of the gravity anomaly below the base of the lithosphere, the first suggesting the anomalous mass could be made of eclogite, the second that it could be generated by a convective drawdown caused by chemical density depletion of the lithospheric mantle and related to the African Superswell of Nyblade & Robinson (1994). Recently, Kadima *et al.* (2010, 2011) mapped a NW–SE elongated positive and narrow residual gravity anomaly related to a post-rift event before basin subsidence, aligned with the Sembe-Ouesso and the Mbuji-Maji rift sequences that outcrop respectively to the NW and the SE of the Congo basin. This supports the Neoproterozoic rift origin of the basin as earlier postulated by Daly *et al.* (1992).

STRATIGRAPHIC EVOLUTION

As the Congo Basin lies for its larger part within the DRC, the knowledge of its stratigraphy also depended on the progressive geological exploration conducted in this country. Before the first subsurface exploration period with the geophysical acquisitions and drillings, its stratigraphy was inferred from the succession of formations outcropping at its periphery, assuming that they were continuous over large distances (Veatch, 1935; Cahen, 1954; Cahen & Lepersonne, 1954). The sedimentary succession of the area was first recognized by two stratigraphic wells (Samba and Dekese wells) drilled in 1955 and 1956 by REMINA that terminated in red arkoses of Late Neoproterozoic to Early Paleozoic age. The litho-stratigraphic scale of Cahen *et al.* (1959, 1960) was later refined by Lepersonne (1974a, 1974b, 1977), taking into account the results of various studies on the Samba and Dekese drill holes and outcrop data.

Two exploration wells (Mbandaka and Gilson) were later drilled in 1981 by ESSO Zaire, and bottomed in the Neoproterozoic (ESSO Zaïre SARL, 1981a, 1981b). Combining surface geology with well information, Daly *et al.* (1992) presented a single composite stratigraphic column in order to illustrate their views of the tectono-stratigraphic evolution of the basin. This column is however too generalized to be useful here as it interpolates various stratigraphic units which are discontinuously observed within the *c.* 1200 km wide Congo Basin and which are loosely correlated. In addition, time control is largely lacking for the pre-Karoo deposits and some units have restricted lateral extension, lateral facies change or may be missing in place.

An updated stratigraphy of the Congo Basin is presented hereafter, integrating the knowledge gained from the 4 wells and presenting possible correlations with outcrop data (Fig. 3a and b). As limited seismic and well data are available for understanding the stratigraphic and tectonic evolution of the deeper part of the Congo Basin, a large part of the knowledge of the Neoproterozoic and Phanerozoic has been gained from the study of outcropping units. The Late Paleozoic to Recent sediments are better represented in the wells and paleontologically dated, making the correlations with the outcrops more secure.

Neoproterozoic to early Paleozoic

The stratigraphy of the Neoproterozoic to Early Paleozoic sediments which have been considered in the past to form the basement of the Congo Basin, is complex, sometimes poorly known and with few age constraints. The sedimentary successions vary from one region to another, assembled in Groups and Supergroups (Fig. 3a) as compiled by Cahen (1954); Lepersonne (1974a, b, 1977), Alvarez (1995), Cailteux *et al.* (2005).

The Neoproterozoic to early Paleozoic sediments outcrop in several large regions surrounding the Congo Basin, each with its own characteristics (Cahen, 1954; Lepersonne, 1974a, b, 1977; Alvarez, 1995 and Cailteux *et al.* (2005). For the Cryogenian, Ediacaran and early Paleozoic periods, they are assembled in three major regionally distinct Groups (Figs 2 and 3a, c):

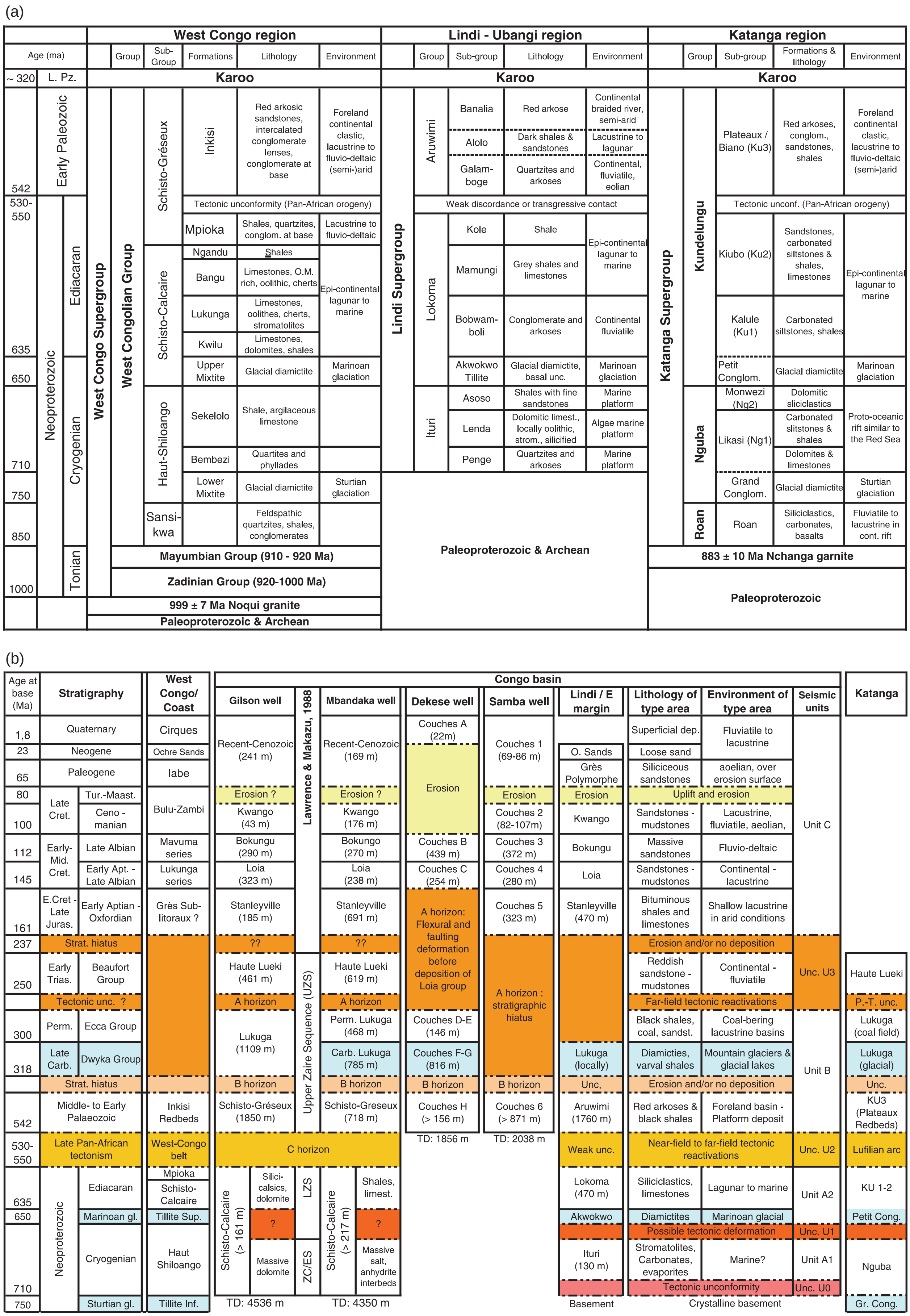
- to the SW, the West Congolian Group as part of the West Congo Supergroup in the West-Congo orogenic belt, resting over Paleoproterozoic to Archean and the Noqui granite dated at 999 ± 7 Ma (Tack *et al.*, 2001; Frimmel *et al.*, 2006).
- to the N and NE, the mostly tabular Lindi Supergroup (Verbeek, 1970; Thibaut, 1983);
- to the SE, the Katanga Supergroup in the Lufilian arc/Katangan orogenic belt (Robert, 1956; François, 1974; Cailteux *et al.*, 2005; Batumike *et al.*, 2006), resting above a Paleoproterozoic magmatic arc sequence and the Nchanga granite intrusion dated at 883 ± 10 Ma (Master *et al.*, 2005) and extending up to ~535 Ma (John *et al.*, 2004; Armstrong *et al.*, 2005).

In addition, sediments of the Itombwe Supergroup in the Kivu region in eastern DRC are considered as time-equivalent to the former groups (Cahen *et al.*, 1979; Walemba & Master, 2005).

Older low-grade to nonmetamorphic poorly dated sediments of pre-Sturtian age and attributed to the Early Cryogenian–Tonian are assembled into:

- the Mayumbian and Zadinian Groups in West-Congo (lower part of the West Congo Supergroup), composed of volcanic and volcaniclastic, and dated respectively 910–920 Ma and 920–1000 Ma (Frimmel *et al.*, 2006);
- the Mbuji-Mayi (fomer Bushimay) Supergroup in the Kasai, southeast of the Congo Basin, preliminary estimated at 900–1050 Ma (Raucq, 1957; Cahen *et al.*, 1984) but whose time-equivalence with the Roan Group in Katanga cannot be excluded (Cahen, 1970 and Bertrand-Sarfati, 1972);
- The poorly defined Liki-Bembian Supergroup with dominantly siliciclastics and basic volcanics, outcroping on the north-eastern side of the Congo basin (Figs 2 and 3c) in the Liki-Bembe basin (Lepersonne, 1974b; Poidevin, 1985) and in the Sembe-Ouesso basin along the Sangha and Dja rivers (Gérard, 1958; Vicat & Vellutini, 1987; Poidevin, 1985).

The West-Congo and Katanga Supergroups have been respectively involved in the West Congo and Lufilian (or Katangan/Zambezi) orogenic accretionary belts at the western and south-eastern margin of the Congo Basin (West Congo belt: Alvarez *et al.*, 1995; Tack *et al.*, 2001; Kanda-Nkula *et al.*, 2004; Frimmel *et al.*, 2006; Pedrosa-Soares *et al.*, 2008; Lufilian arc: Porada & Berhorst, 2000; Armstrong *et al.*, 2005; Cailteux *et al.*, 2005; Rainaud *et al.*, 2005). In their foreland, these deposits remained relatively tabular but their uppermost sequences composed of continental red beds (Inkisi in the West-Congolian Group and Plateaux/Biano in the Katanga Supergroup, also referred to as the Redbeds), overlie unconformably the earlier folded sequences (Tack *et al.*, 2008). At both locations, this unconformity likely corresponds to the paroxysm of the Pan-African orogeny, estimated at ≈550 Ma from the coincidence of the paleomagnetic poles of the different blocks composing Central Gondwana (Tohver *et al.*, 2006). The timing of the Lufilian orogeny in Katanga has been recently constrained as spanning ≈600 to 512 Ma (Armstrong *et al.*, 2005), with a possible final stage of collision in the Lufilian arc at ≈530 Ma (John *et al.*, 2004; Rainaud *et al.*, 2005). These Redbeds sequences are therefore post Neoproterozic in age, and can be bracketed between the Early to Middle Paleozoic. They are overlain by the Karoo Group with its base (a glacial diamictite) attributed to the (≈320 Ma) Late Carboniferous (Cahen *et al.*, 1960) on the basis of spore determination and correlation with similar deposits of the Lukuga basin in the DRC. We do not consider here that the presence of acritarchs that have been attributed to the Early Cambrian in the sequence underlying the Redbeds in the Mbandaka well (Daly *et al.* 1992) is


(a)
West Congo region
Lindi - Ubangi region
Katanga region
Age (ma)
Group
Sub-Group
Formations
Lithology
Environment
Group
Sub-group
Lithology
Environment
Group
Sub-group
Formations & lithology
Environment
~ 320
L. Pz.
Karoo
Karoo
Karoo
542
530-550
635
650
710
750
850
1000
Early Paleozoic
Neoproterozoic
Ediacaran
Cryogenian
Tonian
West Congo Supergroup
West Congolian Group
Schisto-Gréseux
Inkisi
Red arkosic sandstones, intercalated conglomerate lenses, conglomerate at base
Foreland continental clastic, lacustrine to fluvio-deltaic (semi-)arid
Tectonic unconformity (Pan-African orogeny)
Schisto-Calcaire
Mpioka
Shales, quartzites, conglom. at base
Lacustrine to fluvio-deltaic
Ngandu
Shales
Bangu
Limestones, O.M. rich, oolithic, cherts
Epi-continental lagunar to marine
Lukunga
Limestones, oolithes, cherts, stromatolites
Kwilu
Limestones, dolomites, shales
Upper Mixtite
Glacial diamictite
Marinoan glaciation
Haut-Shiloango
Sekelolo
Shale, argilaceous limestone
Bembezi
Quartzites and phyllades
Lower Mixtite
Glacial diamictite
Sturtian glaciation
Sansi-kwa
Feldspathic quartzites, shales, conglomerates
Mayumbian Group (910 - 920 Ma)
Zadinian Group (920-1000 Ma)
999 ± 7 Ma Noqui granite
Paleoproterozoic & Archean
Lindi Supergroup
Aruwimi
Banalia
Red arkose
Continental braided river, semi-arid
Alolo
Dark shales & sandstones
Lacustrine to lagunar
Galam-boge
Quartzites and arkoses
Continental, fluviatile, eolian
Weak discordance or transgressive contact
Lokoma
Kole
Shale
Epi-continental lagunar to marine
Mamungi
Grey shales and limestones
Bobwam-boli
Conglomerate and arkoses
Continental fluviatile
Akwokwo Tillite
Glacial diamictite, basal unc.
Marinoan glaciation
Ituri
Asoso
Shales with fine sandstones
Marine platform
Lenda
Dolomitic limest., locally oolithic, strom., silicified
Algae marine platform
Penge
Quartzites and arkoses
Marine platform
Paleoproterozoic & Archean
Katanga Supergroup
Kundelungu
Plateaux / Biano (Ku3)
Red arkoses, conglom., sandstones, shales
Foreland continental clastic, lacustrine to fluvio-deltaic (semi-)arid
Tectonic unconf. (Pan-African orogeny)
Kiubo (Ku2)
Sandstones, carbonated siltstones & shales, limestones
Epi-continental lagunar to marine
Kalule (Ku1)
Carbonated siltstones, shales
Petit Conglom.
Glacial diamictite
Marinoan glaciation
Nguba
Monwezi (Ng2)
Dolomitic siliciclastics
Likasi (Ng1)
Carbonated siltstones & shales
Dolomites & limestones
Proto-oceanic rift similar to the Red Sea
Grand Conglom.
Glacial diamictite
Sturtian glaciation
Roan
Roan
Siliciclastics, carbonates, basalts
Fluviatile to lacustrine in cont. rift
883 ± 10 Ma Nchanga garnite
Paleoproterozoic
(b)
Age at base (Ma)
Stratigraphy
West Congo/ Coast
Congo basin
Gilson well
Lawrence & Makazu, 1988
Mbandaka well
Dekese well
Samba well
Lindi / E margin
Lithology of type area
Environment of type area
Seismic units
Katanga
1,8
Quaternary
Cirques
23
Neogene
Ochre Sands
65
Paleogene
labe
80
Late Cret.
Tur.-Maast.
100
Ceno - manian
Bulu-Zambi
112
Early-Mid. Cret.
Late Albian
Mavuma series
145
Early Apt. - Late Albian
Lukunga series
161
E.Cret - Late Juras.
Early Aptian - Oxfordian
Grès Sub-litoraux ?
237
Strat. hiatus
250
Early Trias.
Beaufort Group
Tectonic unc. ?
300
Perm.
Ecca Group
318
Late Carb.
Dwyka Group
Strat. hiatus
542
Middle- to Early Palaeozoic
Inkisi Redbeds
530-550
Late Pan-African tectonism
West-Congo belt
635
Ediacaran
Mpioka
Schisto-Calcaire
650
Marinoan gl.
Tillite Sup.
710
Neoproterozoic
Cryogenian
Haut Shiloango
750
Sturtian gl.
Tillite Inf.
Recent-Cenozoic (241 m)
Erosion ?
Kwango (43 m)
Bokungu (290 m)
Loia (323 m)
Stanleyville (185 m)
??
Haute Lueki (461 m)
A horizon
Lukuga (1109 m)
B horizon
Schisto-Gréseux (1850 m)
C horizon
Schisto-Calcaire (> 161 m)
Silici-calsics, dolomite
?
Massive dolomite
TD: 4536 m
Upper Zaire Sequence (UZS)
LZS
ZC/ES
Recent-Cenozoic (169 m)
Erosion ?
Kwango (176 m)
Bokungu (270 m)
Loia (238 m)
Stanleyville (691 m)
??
Haute Lueki (619 m)
A horizon
Perm. Lukuga (468 m)
Carb. Lukuga (785 m)
B horizon
Schisto-Greseux (718 m)
Schisto-Calcaire (> 217 m)
Shales, limest.
?
Massive salt, anhydrite interbeds
TD: 4350 m
Couches A (22m)
Erosion
Couches B (439 m)
Couches C (254 m)
A horizon: Flexural and faulting deformation before deposition of Loia group
Couches D-E (146 m)
Couches F-G (816 m)
B horizon
Couches H (> 156 m)
TD: 1856 m
Couches 1 (69-86 m)
Erosion
Couches 2 (82-107m)
Couches 3 (372 m)
Couches 4 (280 m)
Couches 5 (323 m)
A horizon : stratigraphic hiatus
B horizon
Couches 6 (> 871 m)
TD: 2038 m
O. Sands
Grès Polymorphe
Erosion
Kwango
Bokungu
Loia
Stanleyville (470 m)
Lukuga (locally)
Unc.
Aruwimi (1760 m)
Weak unc.
Lokoma (470 m)
Akwokwo
Ituri (130 m)
Basement
Superficial dep.
Fluviatile to lacustrine
Loose sand
Siliciceous sandstones
aoelian, over erosion surface
Uplift and erosion
Sandstones - mudstones
Lacustrine, fluviatile, aeolian,
Massive sandstones
Fluvio-deltaic
Sandstones - mudstones
Continental - lacustrine
Bituminous shales and limestones
Shallow lacustrine in arid conditions
Erosion and/or no deposition
Reddish sandstone - mudstones
Continental - fluviatile
Far-field tectonic reactivations
Black shales, coal, sandst.
Coal-bering lacustrine basins
Diamicties, varval shales
Mountain glaciers & glacial lakes
Erosion and/or no deposition
Red arkoses & black shales
Foreland basin - Platform deposit
Near-field to far-field tectonic reactivations
Siliciclastics, limestones
Lagunar to marine
Diamictites
Marinoan glacial
Possible tectonic deformation
Stromatolites, Carbonates, evaporites
Marine?
Tectonic unconformity
Crystalline basement
Unit C
Unc. U3
Unit B
Unc. U2
Unit A2
Unc. U1
Unit A1
Unc. U0
Haute Lueki
P.-T. unc.
Lukuga (coal field)
Lukuga (glacial)
Unc.
KU3 (Plateaux Redbeds)
Lufilian arc
KU 1-2
Petit Cong.
Nguba
Gr. Cong.

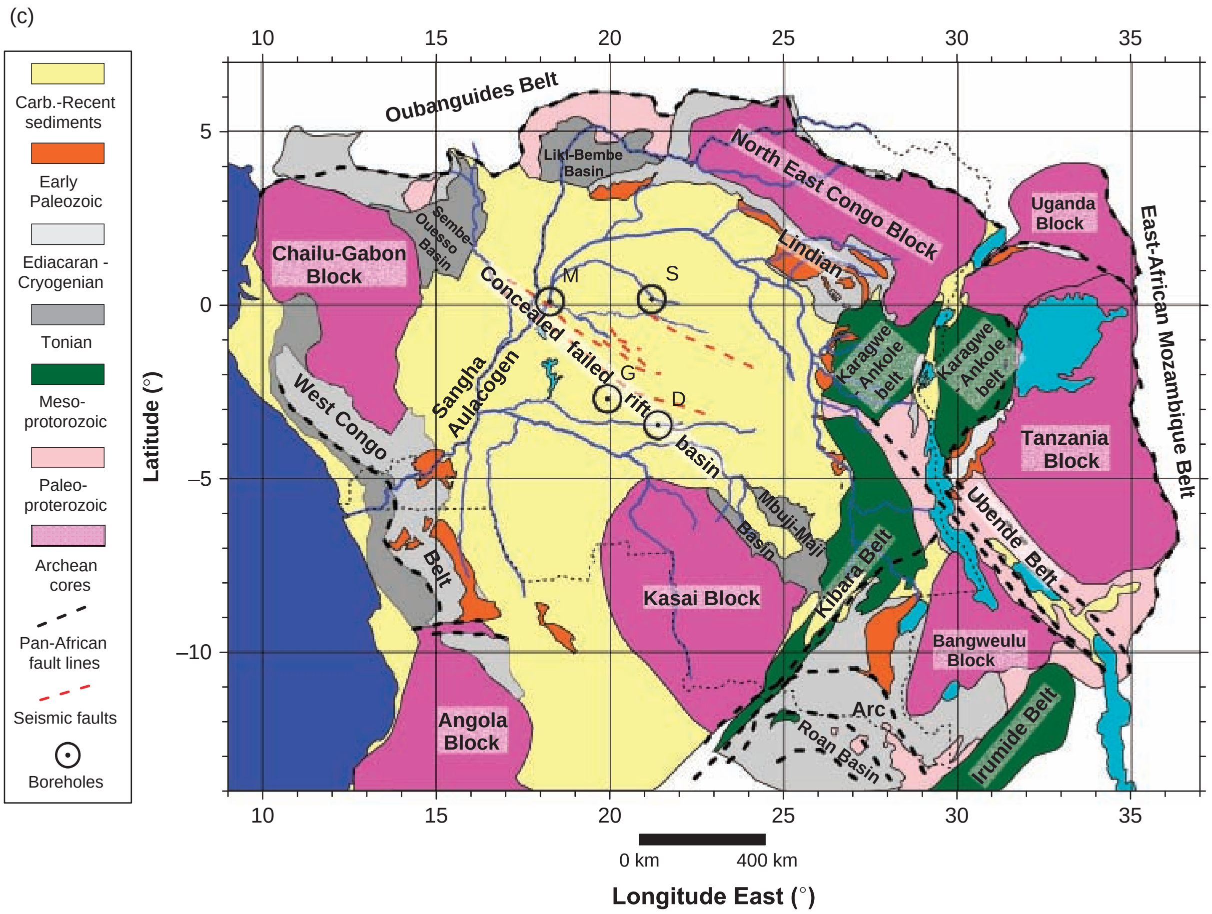


Fig. 3. continued

convincing enough to suggest an Ordovician to Devonian age for the Redbeds, but this cannot be excluded.

Away from the deformed West-Congolian and the Katangan foreland regions, and in the basin margin (Lindi region), the Redbeds are seen overlying in an apparent concordance the subtabular older sequences (Lepersonne, 1974a, b; Tack *et al*., 2008). Therefore, the Pan-African unconformity can be difficult to identify.

The tabular forelands of both Pan African belts extend from the outer rim towards the inner part of the Congo Basin and, like for the Lindi Supergroup, dip gently underneath the Karoo to Recent sequences over long distances. These deposits thus display a centripetal structural and sedimentary polarity. Attempts at lithostratigraphic correlations have been ongoing for decades, mainly based on similarities in lithology (e.g. the glaciogenic diamictites; e.g. Cahen, 1963, 1982). However, age differences of *c*. 200 My may exist between similar rock types from different regions (e.g. the association of stromatolites and silicified oolitic rocks in the Katanga- and West Congo Groups; Kanda-Nkula *et al*., 2004). This fact indicates that similar depositional paleo-environments may have existed diachronously during the Neoproterozoic in various places of the Congo Basin. Therefore, strict lithostratigraphic

Fig. 3. (a) Lithostratigraphic synthesis for the Neoproterozoic–Early Paleozoic period. Compiled after various authors (see text). Dotted lines between Banalia, Alolo and Galamboge formations: stratigraphic transition by recurrences. (b) Lithostratigraphic columns for the Congo Basin established using data from the 4 wells in the central part of the basin and outcrops on its NE margin (Lindi-Ubangi and Kisangani–Kindu region), compared with the West-Congo and Katanga stratigraphy. Compiled after various authors (see text). Definition of the seismostratigraphic units and unconformities. (c) Tectonic setting of the Neoproterozoic basins of present-day Central Africa, compiled from the 1 : 2 M geological map of the Zaire (Lepersonne, 1974a) and the 1 : 4 M map Geology and Major Ore Deposits of Africa (Milesi *et al*., 2006). The highlighted continental mass, often surrounded by deformation zones, corresponds to the large Congo craton, formed by Archean cores welded together by Paleoproterozoic belts. To be complete, it should include also the Sao-Francisco in block in Brazil, now drifted apart by the opening of the Atlantic. The Karagwe-Ankole and Kibara belts represent a Mesoproterozoic intracratonic tectono-magmatic event (Tack *et al*., 2010). In the Lufilian Arc, fragments of the Roan Group (early Cryogenian) have been involved in the Late Pan-African deformation and could be eventually be time-equivalent to the upper part of the Mbuji-Maji Supergroup. Autochtonous remnants of the Roan Group (Roan Basin) are located in the internal part of the Lufilian Arc.

correlations among the three Supergroups will only be possible, provided enough well-constrained age determinations of critical rock types have been obtained in each separate lithostratigraphic column.

Despite these limitations, a tentative long-distance correlation and age calibration is proposed in Fig. 3a, based on the recognition of a series of major tectono-stratigraphic events that are supposedly coeval in time for the three major sedimentary sequences outcropping along the rim of the Congo Basin: i.e. the West Congolian Group and the Lindi and Katanga Supergroups. As it can be hazardous to perform correlations on the basis of lithological facies only, the major glacial events have been used instead, accepting the 'Snowball Earth' theory following which the Cryogenian glaciations are global and thus contemporaneous (Hoffman & Schrag, 2002). Other authors argue however that the glacial deposits are related to tectonically control uplifted block and are therefore not necessary contemporary (Eyeles & Januszczak, 2004). In absence of better age constraints, we tentatively accept that these glacial events are contemporary at the scale of Central Africa. The Cryogenian part of the Neoproterozoic is characterized by several major glacial events, with the Sturtian (750–710 Ma) and the Marionan (650–635 Ma) as the most prominent ones (Hoffman & Schrag, 2002; Hoffman *et al*, 2004; Hoffman & Li, 2009).

In West Congo as in the Katanga region, diamictites associated to the Sturtian and Marionan glaciations have been identified respectively as Tillite Inférieure and Grand Conglomerat for the Sturtian event and as Tillite Supérieure and Petit Conglomerat for the Marinoan period. Following Master *et al.* (2005), the Petit Conglomerat and its overlying cap carbonate (Calcaire rose) might be correlated with the Ghaub diamictite in the Damara orogen, dated at 650–635 Ma by Hoffman *et al.* (2004). In the Lindi Supergroup, the Akwokwo tillite also corresponds to a glacial diamictite (Delpomdor & Tack, 2007). As only one diamictite level is known in the Lindian, it can be correlated either to the Sturtian or to the Marinoan event. A 730–755 Ma depositional age has been estimated by Poidevin (2007) on the basis of Sr-geochronometry, suggesting it could correspond to the Sturtian. We favour however a Marionan age because, on the basis of detailed field descriptions of Verbeek and the rock archive stored in the Royal Museum for Central Africa, it was found that the Akwokwo tillite appears in direct association with typical 'cap carbonates' (Tait *et al.*, 2010). This succession of glacial diamictites surmounted by pink coloured dolomites ('cap carbonates') is characteristic for the Marionan glaciation (Hoffman *et al.*, 2004; Shields, 2006).

As discussed above, the tectonic unconformity related to the paroxysm of the Pan-African orogeny (550 Ma) separates the uppermost deposits (Inkisi in West Congo, Aruwimi within the basin and Plateaux/Biano in the Katanga) from the lower ones.

Using these tectono-stratigraphic events as markers, the West Congolian Group is subdivided into the Sansikwa, Haut-Shiloango, Schisto-Calcaire–Mpioka and Inkisi Subgroups (Fig. 3a). Stratigraphically below the Sturtian diamictites, the Sansikwa Subgroup in West Congo could be equivalent to the Roan Group in Katanga but has no equivalent in the Lindi–Ubangi region. The upper part of the Mbuji-Maji Supergroup could eventually also be equivalent to them. Between the Sturtian and the Marionan diamicties, the Haut-Shiloango Subgroup of West Congo is time-equivalent to the Ituri Group in the Lindi region and to the Nguba Group in Katanga, but is missing in the Ubangi region. The Sansikwa Subgroup in West Congo and the Roan Group of Katanga are both capped by a Sturtian glacial diamictite, respectively the Lower Diamictite/Tillite and the Grand Conglomerat. Above (or starting with) the Marinoan glacial diamictites, the Schisto-Calcaire of West Congo correlates with the Lokoma Group of the Lindian and the lower and middle Subgroups of the Kundelungu Ku1 (Kalue) and KU2 (Kibuo).

Above the Pan-African unconformity, the *c.* 1000 m thick tabular fluvio-deltaic red arkoses (Redbeds) can be found, defined as the Inkisi Subgroup in West Congo (Alvarez *et al.*, 1995), the Aruwimi Group in the Lindi–Ubangi region (Verbeek, 1970) and the Upper Kundelungu (Ku3) in the foreland of the Katanga belt. For the latter, it has been described as 'Plateaux' Subgroup (Lepersonne, 1974a, 1974b; Dumont *et al.*, 1997; Dumont & Hanon, 2000; Cailteux *et al.*, 2005; Batumike *et al.*, 2006) and recently renamed 'Biano' Subgroup by Batumike *et al.* (2007) and Haest *et al.* (2007). Ar-Ar dating of detritical muscovites form this unit by Master *et al.* (2005) gave a maximum age of 573 Ma (terminal Edicarian), supporting the idea that it has been deposited in the foreland of the Lufilian orogen. A similar detrical zircon age of 565 Ma was obtained for the Inkisi formation of West Congo (Frimmel *et al.*, 2006). The depositional environment of the Redbeds are largely continental, lacustrine to fluvio-deltaic semi-arid, with lacustrine to lagunar at the center of the basin (Alolo shales), in a very large platform-like depression spanning the whole Congo Basin and grading into foreland basins on its rim.

In the Lindi Supergroup, the Aruwimi red arkoses overlie the Lokoma Group with a weak discordance or transgressive contact. Within the Aruwimi itself, the ~100 m thick dark Alolo shales and sandstones represent a lacustrine to lagoon interval between the continental Galamboge (~100 m thick) and Banalia (~1000 m thick) arkoses of respectively semi-arid fluviatile to aeolian and braided river facies. As the transition between these formations is gradual, it seems justified to associate these three formations to the Aruwimi Group rather than correlating only the Banalia red arkoses with the Inkisi and Plateaux/Biano units as proposed by Tait *et al.* (2010).

The sedimentary successions in the Liki-Bembe and the Sembe-Ouesso basins are remarkably similar and have been parallelized by Gérard (1958) and Poidevin (1985). They comprise quartzites, slates and conglomerate at the base, and calcareous shales and limestones with levels of black shales. In the Sembe-Ouesso basin, these series are capped by the Dja tillite (Cryogenian) and affected by two episodes of dolerite intrusions (Vicat & Vellutini, 1987; Poidevin, 1985). The first period of intrusion occurred before the Dja tillite and corresponds to intraplate magmatism while the second one post-dates the tillite and is of oceanic affinity. Vicat & Vellutini (1987) interpret this basin as a failed rift, later involved in compressive tectonics.

Evidence for Neoproterozoic evaporites

During the Neoproterozoic, several basins framing the Congo craton and also inside the craton, formed in an extensional (rift) context and developed partly in restricted coastal plain, and rift environment.

In the West-Congolian Group of Bas-Congo, the Schisto-Calcaire Subgroup has been deposited in a shallow carbonate shelf environment rich in algal mats, with stromatolites, limestones and dolomudstones with cherts, oolites and sulphates, (Delpomdor *et al.*, 2008). The presence of early diagenetic sulphate suggests subtidal restricted lagoons evolving into a sabhka environment. In South Gabon, a shallow subtidal to supartidal evaporitic environment is also evidenced for the Schisto-Calcaire by pseudomorphosed relicts of gypsum and anhydrite (Préat *et al.*, 2010). The carbonates precipitated from sulphate-rich hypersaline waters and were subsequently dolomitized and silicified during diagenesis.

In the Mbuji-Mayi basin, similar rocks are found in a rift-like setting, with stromatolites and dolomudstones with cherts and oolites (Raucq, 1957). Recognition of abundant pseudomorphosed relicts of sulphates allows Delpomdor (personal communication) to propose a similar environment as for the Schisto-Calcaire. The carbonaceous formations of the Mbuji-Maji region contain the largest variety of stromatolites that can be compared with the northern border of the Taoudeni basin (Bertrand-Sarfati, 1972).

In the Katanga Supergroup, the Roan carbonated-pelite dominated sediments form the basal Subgroup of the Katanga Supergroup, below the Grand Conglomerat which represents the Sturtian glaciation (750–710 Ma). As compiled by Jackson *et al.* (2003), several lines of evidence including pseudomorphs of gypsum and anhydrite, chlorite inclusions in ores and saline springs, point to a sabhka environment.

The stromatolites from the West-Congo and Lindi regions are restricted to a small number of species and forms, with a possible correlation of the Lenda limestones of the Ituri Group (Lindi Supergroup) with the upper part of the Mbuji-Maji Supergroup (Bertrand-Sarfati, 1972).

In the Congo Basin itself, well and geophysical evidence also suggest the presence of deep-lying evaporites in the Neoproterozoic sedimentary section (this paper).

Karoo Group

The Karoo Group in the DRC (Figs 2 and 3b) comprises the Lukuga formation and overlying Haute Lueki Formation (Lepersonne, 1977; Cahen & Lepersonne, 1978).

The Lukuga formation is preserved in tectonic grabens related to the East African rift, in the Lukuga basin along the border of Lake Tanganyika (Fourmarier, 1914), in the Luena basin in the Upemba depression of Central Katanga (Cambier, 1930), in *U*-shaped glacial valleys on the eastern margin of the Congo Basin (Boutakoff, 1948) as well as in the Dekese sub-basin of the Congo Basin (Cahen *et al.*, 1960). Its base displays typical diamictites and varval clay of the Gondwana glaciation, equivalent to the 'Dwyka Conglomerates' diamictites of the Karoo type locality in South Africa, attributed to the Late Carboniferous ($\approx$320 Ma). The remaining part of the Lukuga formation is represented by post-glacial claystones and sandstones (Dekese sub-basin) and coal-bearing measures (Lukuga and Luena grabens), correlated to the Ecca Subgroup of South Africa (Daly *et al.*, 1991; Catuneanu *et al.*, 2005; Johnson *et al.*, 2006).

The Haute Lueki formation is present along the eastern margin of the Congo Basin, overlying the Lukuga formation with a slight unconformity (Fourmarier, 1914; Lepersonne, 1977). The base of the Haute Lueki formation has been paleontologically dated as Early Trias, equivalent to the Beaufort Subgroup of South Africa (Johnson *et al.*, 2006).

Jurassic to Cenozoic continental deposits

The formations of the Karoo Group are capped successively by upper Jurassic Stanleyville formation and Cretaceous and Cenozoic continental deposits (Figs 2 and 3b; Lepersonne, 1974a, b, 1977; Giresse, 2005). A stratigraphic hiatus exists therefore between the Early Triassic Haute Lueki and the Stanleyville formations, encompassing at least the Early Jurassic (Fig. 3b).

The Stanleyville formation occurs as an alternating succession of bituminous shales and limestones (maximum 200 m) deposited in a lacustrine basin in the region south of Kisangani (formerly Stanleyville) and extending along the Congo River in the direction of Kindu until 5°S (Passau, 1923; Lombard, 1960). It has been traversed over 323 m in the Samba well where it is dominantly composed of calcareous sandstones and shales, with only thin bituminous levels (Cahen *et al.*, 1959). A thin (0–20 m thick) lenticular formation of Upper Jurassic, possibly Kimmeridgian age has been also found in wells under Kinshasa and Brazzaville on the western rim of the basin (Egorov & Lombard, 1962). In the Samba well, the Stanleyville formation has been dated as upper Jurassic (Kimmeridgian) on the basis of Ostracods (Grekoff, 1957) and fossil fishes (De Saint-Seine, 1955). Palynological investigations by Stough (1965) have refined its age to Bajocian-Oxfordian.

Sediments from the Cretaceous period are well represented, covering a large part of the Congo Basin (Lepersonne, 1974a, 1974b). They are exposed in the marginal parts of the present-day 'Cuvette' and traversed by all the stratigraphic and exploration wells. They consist of three formations, successively the Loia, Bokungu and Kwango, totalling a maximum of 750 m and covered by a maximum of 200–300 m Cenozoic sediments. These Cretaceous-Tertiary sediments are mostly continental (Giresse, 2005). Dating on the basis of ostracod (Grecoff, 1957), fossil fish (Casier, 1961) and pollen (Boulouard & Calandara, 1963) allows to attribute the Loia formation to the Aptian–Neocomian, the Bokungu formation to the Albian, and the Kwango formation to the Upper Cretaceous (Turonian to Maastrichtian, possibly Cenomanian at base). They are approximately equivalent, respectively to the Lukunga, Mavuma and Bulu-Zambi formation in the coastal basin (Cahen, 1954).

The Tertiary comprises the Paleogene 'Grès Polymorphes' and the Neogene 'Sables Ocres' formations (Cahen, 1954; Lepersonne, 1977; Giresse, 2005), while the Quaternary is represented by superficial deposits.

TECTONIC DEFORMATIONS

The succession of deformation observed on the seismic lines led Lawrence & Makazu (1988) and Daly *et al.* (1991, 1992) to postulate that the initial basin subsidence was initiated by a Late Proterozoic failed rift and subsequent thermal relaxation. This rifting phase could be the consequence of the Rodinia breakup, which subdivided the Congo craton along NW–SE and NE–SW fractures (Hoffman, 1999). As postulated by the same authors, the compressional inversions could be related to the far-field effects of two tectonic events causing the assembly of the Gondwana continent: the Early Paleozoic Pan-African event (Kennedy, 1964; Kröner *et al.*, 2001), and the Permo-Triassic Gondwanide Andean margin type oblique converging event at the southern margin of Gondwana (Daly *et al.*, 1991; Visser & Praekelt, 1996; Delvaux, 2001a; Newton *et al.*, 2006).

Pan-African early rifting stage

In the Congo Basin, a poorly defined early rifting stage is suggested by Lawrence & Makazu (1988) and Daly *et al.* (1991, 1992) to have controlled the deposition of the 210 m thick carbonate-evaporite sequence, before the deposition of the 700 m thick clastic sequence of the Schisto-Calcaire Subgroup.

A network of Late Neoproterozoic intracratonic tectonic depressions developing within the Congo craton have been proposed to control the Neoproterozoic carbonate sedimentation in Central Africa (Alvarez, 1995). The NE-trending Sangha aulacogen which presently controls the lower course of the Congo river between Mbandaka and the Atlantic ocean could be a dominant extensional structure, linking three belts of NW-trending basins, one centered on the outcropping region of the Lindian north of Kisangani, one centered on the Upper Sangha river in the People's Republic of Congo, the Lukenie river and connected to the Mbuji-Maji and Roan basins, and one corresponding to the West-Congo belt (Fig. 3c). They might not be all contemporaneous, but they are believed to control the depositional histories in the early stage of development of the future Congo Basin. These basins apparently developed as failed rifts (aulacogens) between the Archean blocks of the Congo craton, without reaching the full oceanic stage. They could have been connected to the large rift system that possibly separated the Congo craton from the Kalahari craton, leading to the formation of a passive continental margin on the southern side of the Congo craton (Porada, 1989; Porada & Berhorst, 2000; Burke *et al.*, 2003; John *et al.*, 2004). In the region of the future Lufilian Arc, the WNW-trending Roan rift basin created the adequate environment for the deposition of the evaporate-rich carbonates (Porada & Berhorst, 2000; Jackson *et al.*, 2003). These have been later involved in salt tectonics during the Lufilian orogeny as proposed by John *et al.* (2004). Similarly, the West-Congolian basin, and possibly also the Mbuji-Maji basin also created favorable conditions for carbonate shelf development and evaporate deposition as reviewed above.

The gravity modelling and subsidence analysis of Kadima *et al.* (2010, 2011) further suggest the presence of a large fossil rift concealed under the central part of the Congo Basin and aligned in a NW–SE direction with the Sembe-Ouesso and the Mbuji-Maji failed rift basins (Fig. 3c). This Pan-African rifting stage, not only governed the sedimentation but also created permanently weak zones within the Congo craton, probably by reactivating the fabric of the Eburnean belts that sealed the cratonic cores. This is supported by the significant seismicity recorded within the Congo Basin (international catalogues and Ayele, 2002).

Pan-African near-field collisional stage

The Pan-African cycle terminates with the final amalgamation of continental blocs into the Gondwana continent (Collins & Pisarevsky, 2005; Tohver *et al.*, 2006). This occurred with a series of collisional events that affected different parts of the continent. In Central Africa, the Pan-African deformations surrounding the Congo Craton and affecting the Neoproterozoic deposits of the Congo Basin are known mainly in the southeastern (Katanga) and western (Bas Congo) regions of the Democratic Republic of Congo:

- in the Copperbelt of Katanga and Northern Zambia, the Pan-African event is responsible for the Lufilian Arc which is located approximately 1000 km away from the center of the Cuvette. It is characterized by a compressional regime inducing curved folds, thrusted terranes and shear zones, with its paroxysm at ~550 Ma (Cailteux & Kampunzu, 1995; Porada & Berhorst, 2000; Batumike *et al.*, 2006).
- in the Bas Congo, the Pan-African event is also responsible for the West Congo belt (Fig. 2), which parallels the Atlantic coast between Gabon and Angola, and is located 200–400 km west of the Congo Basin. The intensity of folding and thrusting within the West

Congo belt decreases from west to east (Boudzoumou & Trompette, 1988; Tack *et al.*, 2001; Pedrosa-Soares *et al.*, 2008).

To the NE and SE of the Cuvette, outcropping Neoproterozoic to early Paleozoic sediments are respectively known as the Lindi and Mbuji-Maji Supergroups (Fig. 3c). The first is weakly folded with few synclines or anticlines bounded by high-angle faults whereas the second forms a gentle NW–SE trending syncline affected toward the southeast by Pan-African NNE–SSW-oriented folds (Cahen *et al.*, 1984).

The lower age limit for the paroxysm of the Pan-African orogeny surrounding the Congo Craton is at *c.* 550 Ma, with the final collision at $\approx$530 Ma with later manifestations at *c.* 520 Ma., at the vicinity of the 542 Ma Neoproterozoic–Cambrian transition (Porada & Berhorst, 2000; John *et al.*, 2004; Armstrong *et al.*, 2005; Rainaud *et al.*, 2005).

Gondwanide far-field active margin stage

Some of the compressional structures observed on the seismic profiles have been attributed by Daly *et al.* (1991) to the Late Paleozoic–Early Mesozoic deformation. Within the Lindi Supergroup near Kisangani, Sluys (1945) and Verbeek (1970) describe a narrow WNW–ESE belt of intense deformation involving folding, brittle shearing and metasomatism that affect the whole Lindi Supergroup (including the Aruwimi Redbeds) but which pre-dates the Upper Jurassic and Cretaceous sediments. In the Lukuga coal field near Kalemie along the Congolese side of Lake Tanganyika, Cahen and Lepersonne (1978) describe an unconformity between the Permian sediments of the Lukuga Group and the overlying Triassic sediments of the Haute Lueki Group, thus constraining the age during the Permo-Triassic transition. Further to the northeast, strike-slip deformations due to NNE–SSW to N–S tectonic compression and affecting the Permian coal-bearing Karoo rocks have been noted in the Ubende belt in Tanzania, particularly in the Namwele-Mkolomo coal field (Delvaux *et al.*, 1998; Delvaux, 2001b).

These localized deformations scattered over a wide territory are coeval with the Late Permian–Early Triassic development of the Cape Fold Belt of South Africa (Hälbich *et al.*, 1983; Le Roux, 1995; Newton *et al.*, 2006; Tankard *et al.*, 2009). This belt was part of the Gondwanide passive margin orogen that framed the southern margin of Gondwana and was related to the Paleo-Pacific subduction plate dipping beneath Gondwana during Late Carboniferous to mid-Triassic times (Ziegler, 1993; Visser & Praekelt, 1996; Trouw & De Wit, 1999; Delvaux, 2001a; Giresse, 2005). The contractional deformations identified in the seismic sections of the Congo Basin are also related to the far-field deformation resulting from the distant (roughly 2500 km away) Cape folding event (Daly *et al.*, 1991, 1992). At the same time, an extensional tectonic regime prevailed along the Tethyan northern margin of Gondwana (Wöpfner, 1994; Ring, 1995; Delvaux, 2001a; Catuneanu *et al.*, 2005).

WELL DATA

The two fully cored stratigraphic wells were drilled, in the localities of Samba (2.039 m; Cahen *et al.*, 1959) and Dekese (1.856 m; Cahen *et al.*, 1960) (Fig. 2), reaching the Redbeds at respectively 1.167 and 1.677 m deep but without traversing them entirely.

The exploration wells of Mbandaka (4350 m; Esso Zaïre S.A.R.L., 1981a) and Gilson (4563 m; Esso Zaïre S.A.R.L., 1981b) have been cored only over a few meters. Cuttings were sampled every 10 m but they are no longer accessible (probably lost in the DRC during the political troubles). The Mbandaka well was stopped in massive salt deposits with anhydrite interbeds after encountering stromatolitic carbonates while the Gilson well was stopped in massive dolomite. None of the four wells reached the crystalline basement, evidenced by the seismic reflection profiles and tentatively assigned to the Paleoproterozoic as reviewed above.

Only the Jurassic to Recent sediments encountered in the Dekese (Couches A–C) and Samba (Couches 1–5) wells have been accurately dated paleontologically as reviewed above. Sediments attributed to the Karoo and correlated with the Lukuga formation have been recognized in the Dekese well but are absent in the Samba well. The Haute Lueki formation, outcropping along the eastern margin of the basin, has not been recognized in these stratigraphic wells. In the lower part of both wells, the red arkoses of Couches H (Dekese) and Couches 6 (Samba) have been correlated to the Aruwimi Group.

The stratigraphic information related to the Gilson and Mbandaka exploration wells are unfortunately sparse, as they are provided mainly by cuttings that cannot be accessible anymore for further study. The upper sediments are attributed to the Cretaceous to Recent, but the correlation of the deeper deposits is more problematic. The presence of the Stanleyville and Haute Lueki formations is suggested in the well Geological Completion Reports (Esso Zaïre S.A.R.L., 1981a, 1981b) but is not mentioned explicitly in the E.C.L (1988) report nor in Lawrence & Makazu (1988). Below what Lawrence & Makazu (1988) name as the 'Base Jurassic unconformity', they identify an Early to Middle Paleozoic Upper Zaire Sequence (UZS) separated by the 'Pan-African Unconformity' from the Lower Zaire Sequence (LZS) which itself overlies the Zaire Carbonate/Evaporite Sequence (ZC/ES). The UZS includes indifferently both the Aruwimi and Lukuga Subgroups. In the E.C.L. report, however, the Lukuga formation (dominantly conglomeratic) is identified above successively the 'Infra-Cambrian' Schisto-Greseux, the Schisto-Calcaire and the Carbonate-Evaporite sequences. The Carbonate-Evaporite sequence was not originally differentiated from the rest of the Schisto-Calcaire in the well Geological Completion Reports. This subdivision of the Schisto-Calcaire was proposed by Daly *et al.* (1992) by correlation with the outcropping sections of the Lindian (Verbeek, 1970), referring the upper part (calcareous to dolomitic silciclastics) to the Lokoma Group and the lower part

('Carbonate-evaporite sequence'), to the Ituri Group, separated by a weak unconformity (Fig. 3b).

An important result of the Gilson and Mbandaka wells is the discovery of the presence of evaporites and salt in their deeper parts. In order to prevent possible confusion, we use the term evaporite for designing all the primary minerals formed by direct precipitation from brines (sulfates and halides) and salt as in salt tectonics, for low-density and deformable halite.

The lower part of the Schisto-Greseux sequence in both the Gilson and Mbandaka wells contains thin anhydrite layers, mixed with clay in the Gilson well (Esso Zaïre S.A.R.L., 1981b), and with traces of gypsum in the Mbandaka well (Esso Zaïre S.A.R.L., 1981a).

In the Mbandaka well Geological Completion Report (Esso Zaïre S.A.R.L., 1981a), the upper part of the Schisto-Calcaire is described as composed of dark-grey calcareous to silty shales grading to limestone, the middle part contains argillaceous, dolomitic and stromatolitic limestone, and the lower part is composed of massive salt with anhydrite interbeds, down to the base of the well. The composition of this salt is not mentioned but in petroleum exploration, salt is generally assimilated as halite. In the Gilson well Geological Completion Report (Esso Zaïre S.A.R.L., 1981b), the Schisto-Calcaire is described as an alternating sequence of sandstone, siltstone, shale and dolomite but neither salt nor anhydrite is reported.

SEISMIC REFLECTION DATA

A total of 2900 km of seismic reflection lines have been recorded in an area of $\sim$0.5 M km^2 between the Congo and Kasai rivers, both along rivers (lines R) and roads (lines L) in 1974–1976 by Shell, Texaco and Esso. The locations of the lines are indicated on Figs 2, 7 and 8 and selected parts of the lines are shown in Fig. 9 (L50), 10 (L59), 11 (R13), 12 (R15), 13 (R5).

Using seismic reflection lines calibrated with the four wells and correlated tentatively with outcrop data from the margin of the basin, three major seismo-stratigraphic units can be defined within the Congo Basin (Units A, B, C; Figs 4 and 5). They are resting over the seismic basement and are separated by prominent seismic reflectors

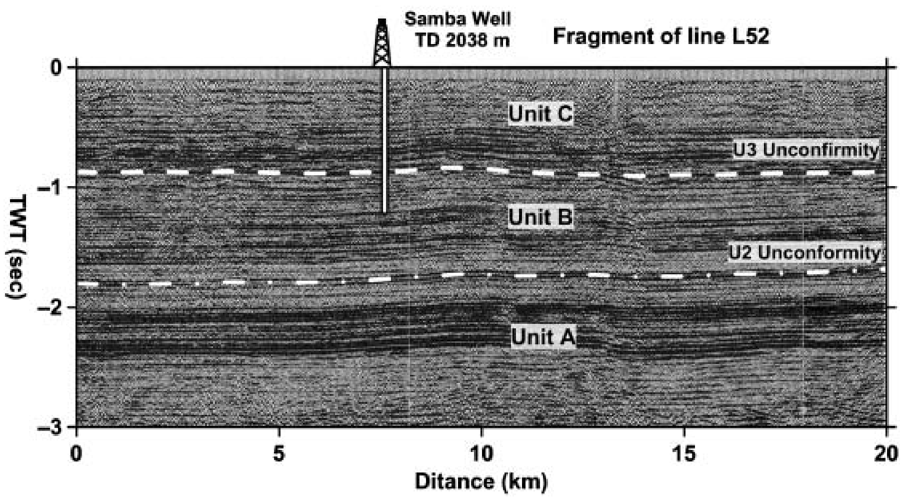


Fig. 4. Calibration of seismic line L52 with the stratigraphic log of Samba well. Seismic units are shown with reference to Fig. 3. Only the fragment of the line at the vicinity of the well is shown.

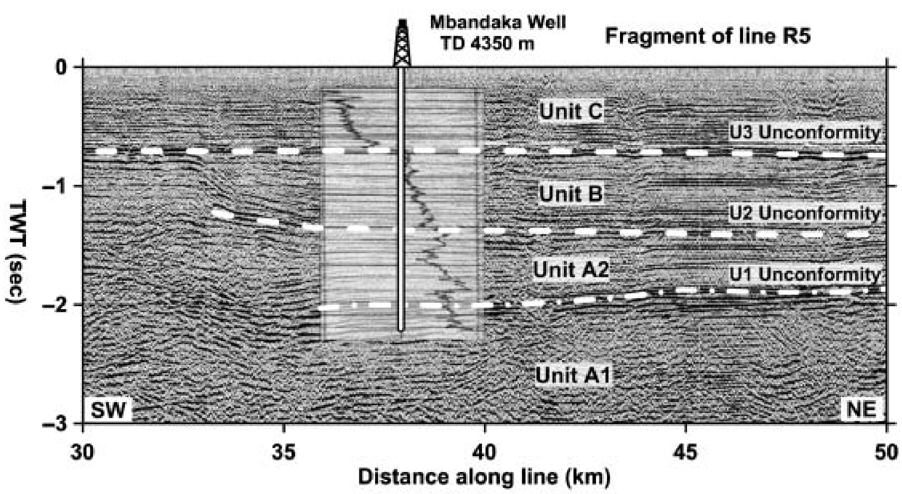


Fig. 5. Calibration of seismic line R5 with the sonic diagraphy of Mbandaka well. Seismic units are shown with reference to Fig. 3. Only the fragment of the line at the vicinity of the well is shown.

corresponding to major regional unconformities (U0–U3). The nature of the seismic basement underneath the basin is unknown, but it is reasonable to infer that it is mainly of crystalline and metamorphic nature, and of pre-Neoproterozoic age. Although four stratigraphic hiatuses are shown on the litho-stratigraphic column of Daly *et al.* (1992), only two major regional unconformities are observed on the majority of the seismic lines, and one more local and deeper (Fig. 3b). Lawrence & Makazu (1988) refer the lower one (U1) as separating the Ituri from the Lokoma Groups, the intermediate one (U2) as the 'Pan-African unconformity' at the Neoproterozoic–Paleozoic transition, and the upper one (U3) as the 'Base Jurassic unconformity'. The latter corresponds to the combination of the 'Late Paleozoic deformation' of Daly *et al.* (1992) and a regional hiatus identified over most of the basin that spans from the end of the Permian, up to the base of the upper Jurassic and which corresponds to the Gondwana peneplaine of King (1963).

These unconformities are clearly marked on the Profile Sonic Velocity (PSV) run in the Mbandaka well (Figs. 4 and 5) and subdivide the stratigraphic sequence of the Congo Basin into three seismo-stratigraphic units, from base to top:

- *Unit A* overlies the crystalline basement (U0 unconformity) and represents Neoproterozoic sedimentary rocks. In the Mbandaka and Gilson wells (Lawrence & Makazu, 1988; Daly *et al.*, 1992), it comprises a 210 m thick carbonate-evaporite sequence at the base of the wells, followed by a 700 m thick siliciclastic sequence. It is deformed by the Pan-African orogeny and truncated by the seismic reflector corresponding to the U2 unconformity. A chaotic seismic facies hampering the identification of the basement is locally observed, but it might at least partly be the result of processing. On the seismic profiles, the two sequences can be differentiated on the basis of their seismic facies, allowing the seismic unit A to be subdivided itself into sub-units A1 (at the base) and A2 (at the top), respectively corresponding to the carbonate-evaporite sequence and the clastic sequence. Compared with the Lindi Supergroup lithofacies defined by Verbeek (1970), these sub-units can be tentatively correlated respectively to the Ituri and the Lokoma Groups, separated by a slight unconformity (U1) (Fig. 3).
- *Unit B* lies above the U2 unconformity and is bounded at its top by the U3 unconformity. It represents with some hiatus the Paleozoic sedimentary sequence. Sediments representing this period crop out mainly to the east of the Congo Basin and are known as the Redbeds (in particular, the 'Banalia arkoses') of the Aruwimi Group (undated upper part of the Lindi Supergroup; Tack *et al.*, 2008) and the Lukuga formation (Carboniferous-Permian). In the Dekese well (Fig. 3b) where it has been proposed by Cahen *et al.* (1960), the transition between the 'Couches G' (tillites and varval clay of the Late Carboniferous Lukuga formation) and the Redbeds of the 'Couches H' appears relatively subtle. Re-examination of the cores stored within the RMCA shows that this transition is marked by a facies change, but without particular discontinuity in sedimentation. No marked discontinuity can be seen and the contact clearly shows that fragments of red sandstones have been reworked and re-deposited within the diamictite at the base of the Lukuga sequence. The bedding has the same 40 to 45° inclination at both sides of this contact. Therefore, questions can be raised whether the red arkoses of the Aruwumi formation progressively grade into the glacial sediments and are thus at least partly Middle Paleozoic in age, or if they are separated by an important stratigraphic hiatus spanning a large part of the Middle Paleozoic. In the seismic sections, these two units cannot be clearly differentiated and do not appear to be separated by a marked reflector. They are therefore treated as a single seismo-stratigraphic unit (B).

The Haute Lueki formation (lower Triassic) which overlies the Lukuga formation is known in outcrop only on the eastern margin of the basin and within the Lukuga basin near Lake Tanganyika, but has not been recognized in the Samba and Dekese wells. Both formations are suspected in the Mbandaka and Gilson wells, but without paleontological confirmation (Esso Zaïre SARL, 1981a, 1981b). Therefore, the position of the Haute Lueki formation in terms of the seismic units is difficult to define, but for reasons explained below, we favor the idea that this formation postdates the Late Paleozoic (Permo-Triassic) deformation event.

- *Unit C* overlies the U3 unconformity and corresponds to Mesozoic and/or Cenozoic sediments. We include in this unit the Haute Lueki formation that we consider to post-date the Permo-Triassic tectonic deformation event. With reference to the succession known in the outcrops surrounding the basin (Lepersonne, 1977), this unit comprises, from base to top: the Mesozoic Haute Lueki, Stanleyville, Loia, Bokungu and Kwango formations, and the Tertiary Grès Polymorphes and Ochre Sands. Unit C is almost flat and un-deformed as shown on the seismic lines.

In summary, according to this threefold seismo-stratigraphic subdivision and accepting that the Haute Lueki formation postdates the Permo-Triassic deformation event, Unit A would be equivalent to the Ituri and Lokoma groups (Ediacaran and Cryogenian), and possibly also the eventual prolongation of the Mbuji-Mayi and Liki-Bembian/Sembe-Ouesso Supergroups (Tonian) under the basin, Unit B would be include the Aruwimi Group and Lukuga formation (Paleozoic) and Unit C, the Stanleyville formation up to the superficial deposits (Meso-Cenozoic) (Fig. 3b).

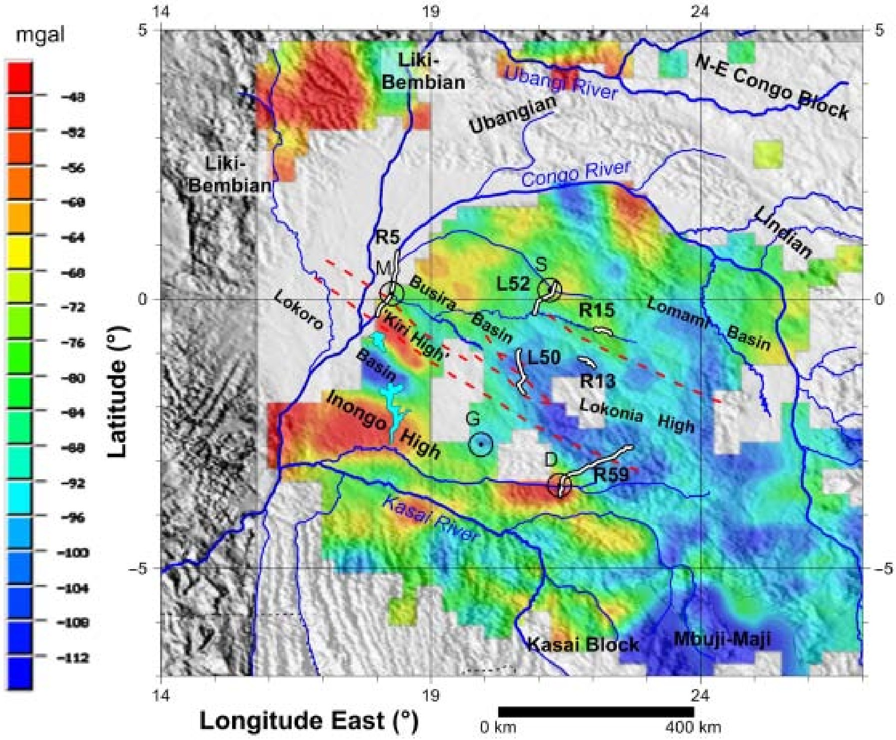


Fig. 6. Bouguer anomaly map of the Congo Basin region as overlay over the shaded-relief Gtopo DEM with the modeled seismic lines. Bouguer density: 2.67 g cm^{-3}; 4 mgal spacing; step grid: 30 km.

POTENTIAL FIELDS

In order to test the hypothesis of Daly *et al.* (1992) that the structures in the central part of the Congo Basin are related to crustal contraction and uplift of a basement block (Kiri High), we reinterpreted the seismic profiles taking into account additional constraints from potential fields (gravity and magnetism).

The Mbandaka and Gilson wells have evidence that the carbonate-evaporite sub-unit A1 locally contains massive salt in addition to anhydrite (ESSO Zaïre SARL, 1981a, 1981b). The models constructed hereafter are designed to investigate the lateral extent of the presence of salt at the base of the basin fill and check the existence of the proposed Kiri High. With gravity data, we expect to identify low-density sediments such as deposits rich in salt and shale and to differentiate them from denser crystalline rocks. Salt-rich formations usually have lower magnetic susceptibilities than shale-rich formations. Hence, on pole-reduced magnetic profiles, salt-rich formations are typically associated with negative magnetic anomalies while shale-rich formations are typically associated with positive magnetic anomalies.

Gravity map

The first gravity measurements in the Congo Basin were acquired by the 'Syndicat pour l'étude géologique et minière de la Cuvette congolaise' (the Syndicate) between 1952 and 1956. A total of 6000 gravity measurements were made at an average interval of 5 km along the rivers and existing roads. Based on these data and using a reduction density value of 2.67 gm cm^{-3} the first map of the Bouguer anomaly was published by Jones *et al.* (1960).

The database used in the present study has been graciously provided by the 'Bureau Gravimétrique International' (BGI) of Toulouse (France). It contains data acquired by the Syndicate, the Lamont Doherty Geological Observatory, the ORSTOM, and the Leopoldville (now Kinshasa) Meteorological Service. A thorough and systematic comparison of 4500 duplicate gravity measurements was made on the various sets of data. This leads to the computation of a root mean square error of ± 0.67 mgal, which is suitable for a regional study and allows the combined use of the different datasets.

The Bouguer anomaly map obtained which has been established from a 30×30 km grid interpolated from the raw data by minimum curvature (0.25 tension factor, 20 extension ratio of surface iteration set, 0.1 convergence limit), shows Bouguer anomaly values ranging between -120 and -20 mgals (Fig. 6). This map is dominated by NW–SE trending anomalies with a wide gravity low centered on the Lokonia High separated from a gravity high on its SW side by a steep gradient, and by a rapid succession of gravity highs and lows along a SW–NE line from the Inongo High to the Busira Basin.

Magnetic susceptibility map

In 1984 a 30 000 km aeromagnetic survey was acquired by Hunting Services Inc. on behalf of JNOC using a Cessna Titan 404 airplane over the central part of the Cuvette, from 2°N to 2°S and from 18 to 26°E, covering

380 000 km^2. The N–S flight and E–W tie lines were respectively flown 18 and 55 km apart, while the altitude was fixed at a constant barometric elevation of 750 m above main sea level. The magnetic data acquired were processed by Nikko Exploration and Development Co to strip the noise and to perform the required correction before producing a Total Field Magnetic map at a 1 : 1 000 000 scale.

We used there already corrected and filtered data by digitizing the map produced by Nikko and compiled a 5 × 5 km LCT grid (Mercator WGS84). The resulting map (Fig. 7) shows a general gradient from the NE to the SW, with sharp variations along WNW-trending lines which might correspond to fault lines.

In order to get the shape anomalies to what would be observed at the pole where the inducing field is vertical, pole reduction was applied to the total magnetic field. Note that the horizontal gradient reduction to pole introduces E–W striping that should not be over-interpreted.

A first horizontal gradient was derived from the resulting map (Fig. 8), showing that the magnitude of the horizontal gradient defines magnetization boundaries and that three major magnetic zones can be individualized:

- a northeastern zone with NW–SE and E–W trending of high magnetic gradient which corresponds to the Lindi Supergroup, possibly covered in part by recent sediments;

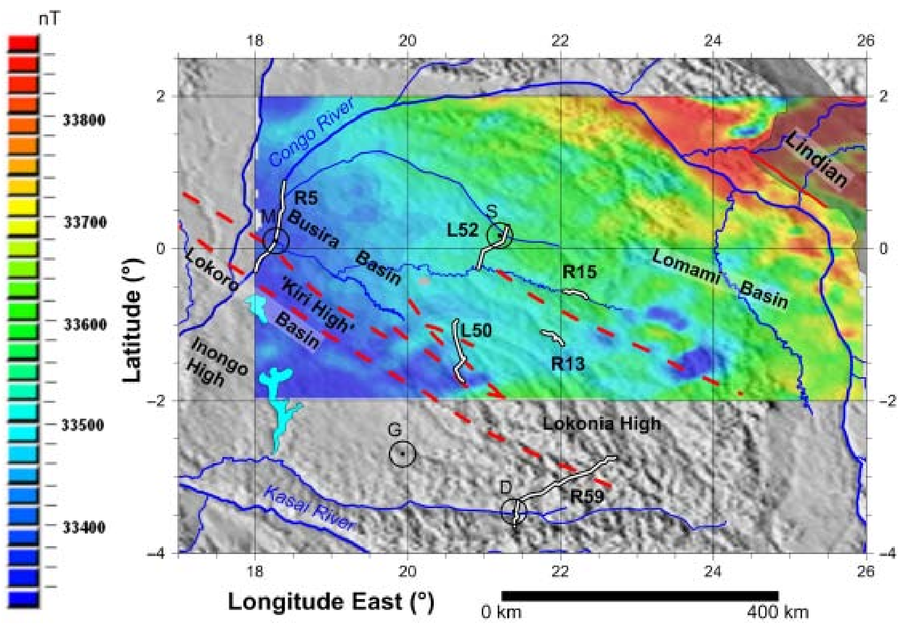


Fig. 7. Total aeromagnetic map of the northern part of the Congo Basin (20 nT spacing; 5 km grid step).

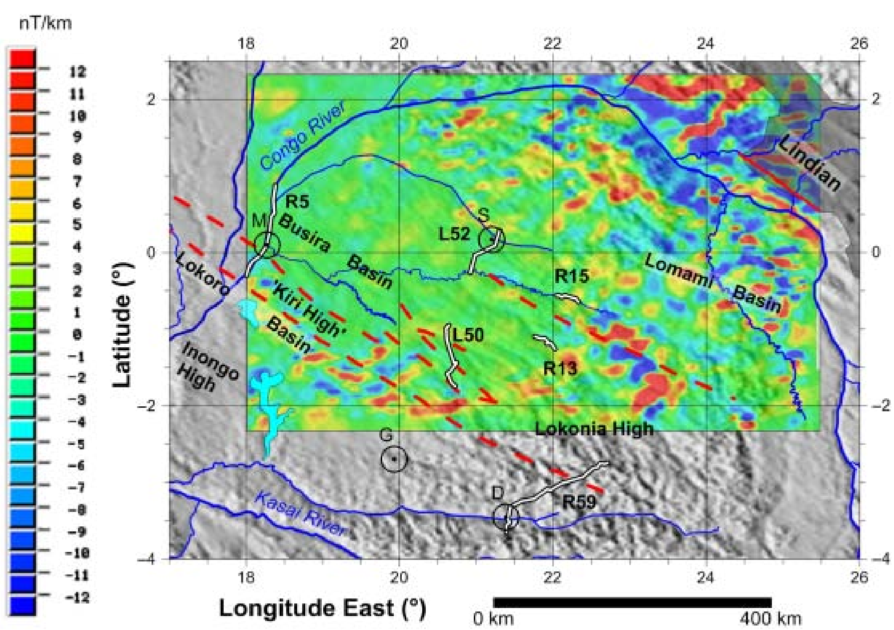


Fig. 8. Horizontal gradient of the pole-reduced aeromagnetic map for the central part of the Congo Basin. 1 nT km^{-1} spacing; step grid: 5 km. Note that the horizontal gradient reduction to pole introduces E–W striping that should not be over-interpreted.

- a central zone dominated by a low magnetic gradient corresponding to the region of deeply buried basement under the Busira Basin;
- a southwestern zone characterized by a moderate magnetic gradient, with a NW-SE magnetic trend in the area where the top of basement is less deep, from the Lokonia High to the Lokoro Basin.

Potential field modeling

To better image the subsurface structure of the basin as well as the deformation taking into account the geometries interpreted from the seismic lines, several potential field models were run and tested.

The quality and validity of the interpretation of gravity data depends on the knowledge of the lateral variation in the density of the rocks. In this study, density values used in the various models were determined from Compensated Neutron Density Logs run in the Mbandaka and Gilson wells, completed by density measured from outcrop samples collected from the different stratigraphic units. The density values obtained are summarized in Table 1.

Magnetic susceptibility was measured by JNOC (1984) on rock samples collected from the Kisangani, Kananga, and the coastal bulge regions, from Cenozoic to Paleoproterozoic in age. The determined magnetic susceptibility values are listed in the Table 2.

The gravity and magnetic data were modeled with the 2-D seismic, Gravity and Magnetic Earth Modeling System using a computer algorithm based on the Talwani method with 2-D polygonal bodies (Talwani *et al.*, 1959). The polygons were generated from seismic horizons and related densities and/or susceptibility were added in the program. Five 2D models have been constructed along selected seismic lines where post-sedimentary deformations are detected. The density and susceptibility values used in the models are summarized in Table 3.

- *Model 1* (Fig. 9) is based on the N-S oriented seismic line L50 located in the centre of the Cuvette (Figs 2 and 6–8). This line illustrates the deformation of the approximately 2000 m thick Unit A, and a later deformation affecting both units A and B. The seismic profile (Fig. 9a) shows in the central part of the basal sedimentary sequence (Unit A), a poorly defined seismic zone marked by a chaotic seismic facies overlying a transparent seismic facies. Within this chaotic seismic facies, structures resembling to folds, contractional faults can be identified below a toplap seismic interface separating it from the overlying Unit B and which defines the unconformity U2. The two units have been later affected by a second deformation, probably related to the Permo-Triassic event. This second event pro-

Table 1. Density values measured and estimated for gravity model

Seismic unit	Lithology	Average density (gm cm^{-3}) Measured (1)	(2)	(3)	(4)	Estimated in models
Unit C	Clastics, Siltstones, rarely Shales	2.09 ± 0.18	2.35 ± 0.1		2.13 ± 0.21	2.25 ± 0.05
Unit B	Clastics, Siltstones, Tillites, rarely Shales	2.47 ± 0.05	2.51 ± 0.1			2.45 ± 0.05
Unit A	Clastics, Shales, Limestone, Salt, Anhydrite	2.57	2.68	2.54	2.42 ± 0.22	2.55 ± 0.05
Crystalline basement	Undifferentiated Crystalline rocks			2.73	2.69 ± 0.16	2.70 ± 0.03

(1) Compensated Neutron Density Log from Gilson (Esso Zaïre SARL, 1981a), (2) Compensated Neutron Density Log from Mbandaka (Esso Zaïre SARL, 1981b); (3) Samples measurements after JNOC (1984); (4) Samples measurements after Unocal (1986).

Table 2. Magnetic susceptibility ($\times 10^{-6}$ e.m.u.) measurements from the study area (JNOC, 1984)

Rock type	Number of samples	Minimal value $\times 10^{-6}$ e.m.u.	Maximal value $\times 10^{-6}$ e.m.u.	Average $\times 10^{-6}$ e.m.u.
Sandstone	33	9	143	49
Limestone	6	42	82	60
Silt	4	25	50	36
Quartzite	9	6	87	34
Granite	10	50	1118	470
Granodiorite	6	28	2202	1094
Schist	13	51	2195	695
Shale	7	36	75	53

(4): Number of samples.

Table 3. Densities ρ (g cm^{-3}) and magnetic susceptibility ($\times 10^{-6}$ e.m.u.) values used in the models for the different units

Units	Models 1a and 1b		Model 2	Model 3		Model 4		Model 5	
	g cm^{-3}	$\times 10^{-6}$ e.m.u.	g cm^{-3}	g cm^{-3}	$\times 10^{-6}$ e.m.u.	g cm^{-3}	$\times 10^{-6}$ e.m.u.	g cm^{-3}	$\times 10^{-6}$ e.m.u.
C	2.3	48	2.3	2.3	48	2.3	48	2.3	48
B	2.46	56	2.54	2.37	103	2.35	87	2.46	56
A									
A2	2.58	59		2.53	102	2.54	104	2.58	59
A1				2.45	0.2–0	2.47	0.2–0		
Seismic basement	2.67	792	2.67/2.77	2.67	648	2.67	590	2.67/2.7	792

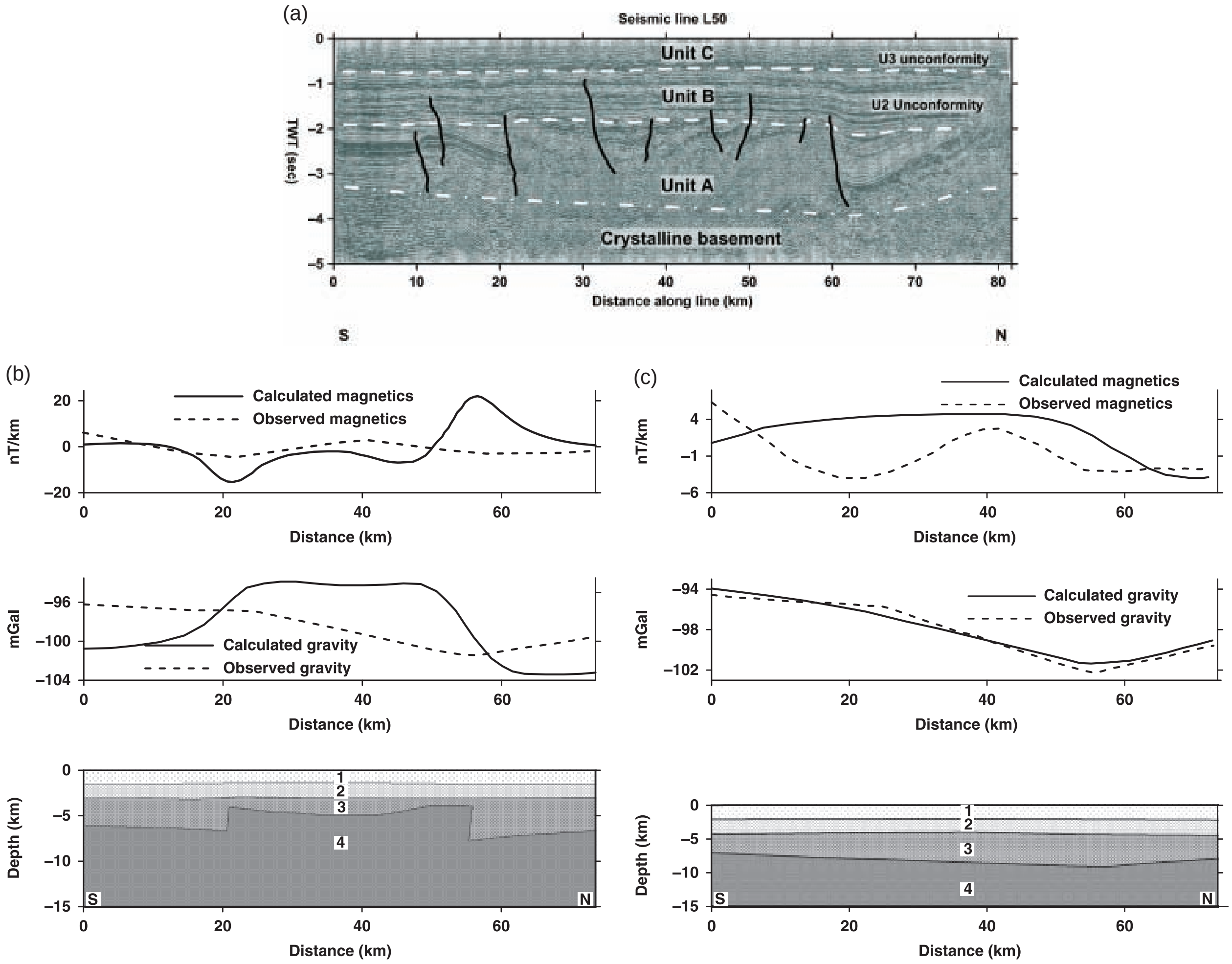


Fig. 9. (a) Interpreted entire seismic line L50 (N–S, in the center of the Cuvette, Fig. 2 and 6–8) illustrating major unconformities, faults and a poorly defined seismic zone marked by a chaotic seismic facies overlying a transparent seismic facies in the center of the profile. In the light of the results of gravity and magnetic modeling, these characteristic seismic facies and deformations are interpreted as a collapsed salt structure (see discussions). The Gondwana and Pan-African unconformities separate the seismo-stratigraphic units A, B and C as defined in Fig. 3. (b) Model 1a (seismic line L50): 2D potential field models along the same line, case when a basement high is considered. Note a mismatch between measured and modeled gravity curves for this case. Polygons: 1, Unit C; 2, Unit B; 3, Unit A; 4, Basement. Densities and susceptibilities are given in Table 3. (c) Model 1b (seismic line L50): 2D potential fields models showing a good match between modeled and measured curves with a non uplift basement hypothesis. Note the higher frequency and amplitude magnetic anomaly related to the induced magnetization in the poor seismic definition zone. Polygons: 1, Unit C; 2, Unit B; 3, Unit A; 4, Basement. Densities and susceptibilities are given in Table 3.

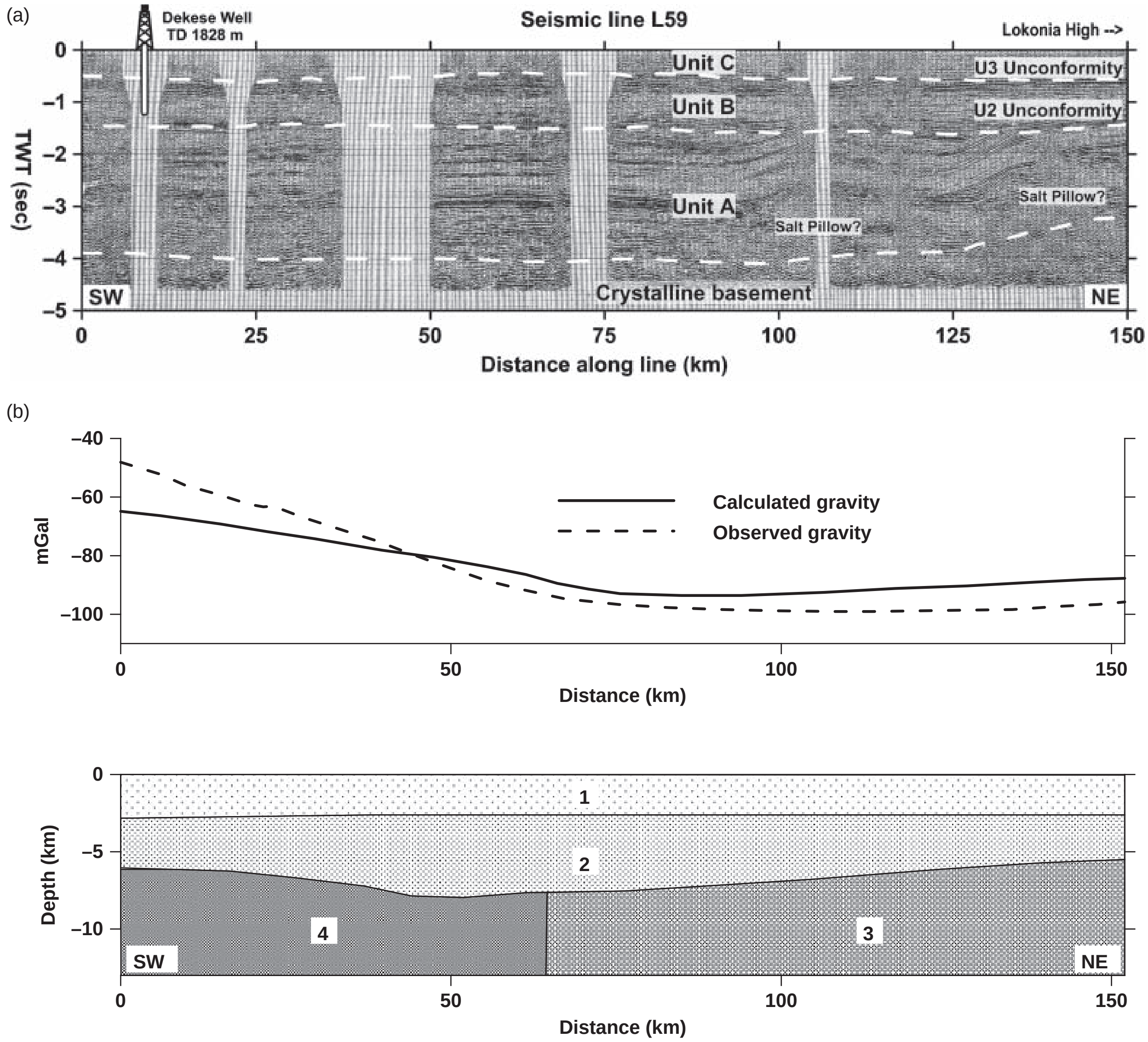


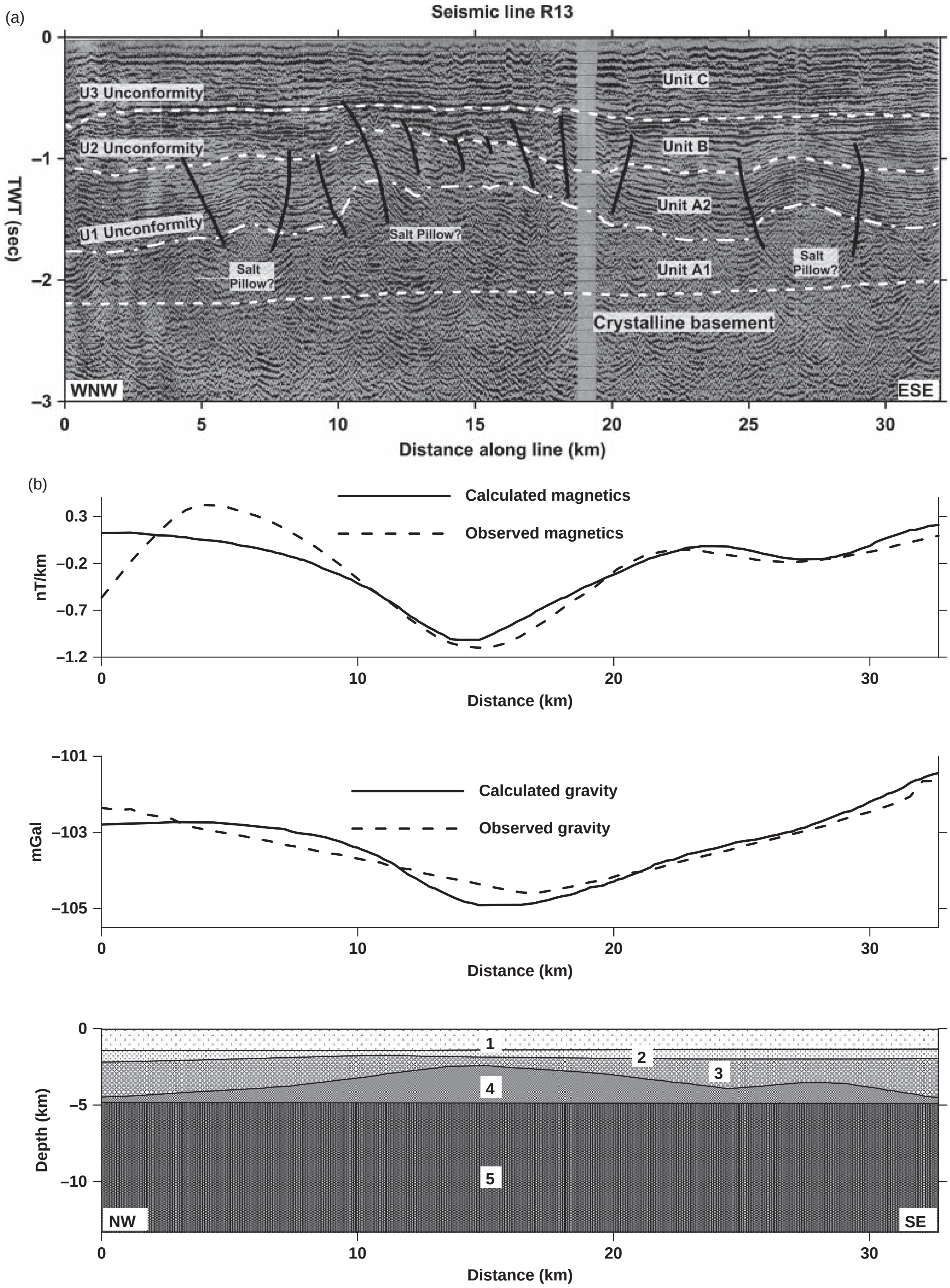
Fig. 10. (a) Interpreted entire seismic line L59 (NE–SW, in the region of the Dekese well, Fig. 2 and 6–8) illustrating major unconformities and anticlinal flexures possibly rooted on salt pillows. The Gondwana and Pan-African unconformities separate the seismo-stratigraphic units A, B and C as defined in Fig. 3. (b) Model 2 (seismic line L59): 2D gravity models showing a good match between modeled and measured curves obtained with a lateral variation of density in the basement which suggested variation in velocity. Polygons: 1, Unit C; 2, Units B and A; 3, Basement 1 (2.67 g cm^{-3}); 4, Basement 2 (2.77 g cm^{-3}). Densities and susceptibilities are given in Table 3.

duced weak deformations in Unit B, mainly in apparent reactivation of the underlying dislocation zones. It might also be responsible for the transparent seismic facies seen on the northern end of the seismic profile.

This poorly defined seismic zone in the center of the profile has been interpreted by Daly *et al.* (1992) as an uplifted basement linking the Lokonia and Kiri Highs and bounded laterally by high-angle reverse faults, grading at depth towards low-angle thrusts. To test this hypothesis, we modeled the gravity along this seismic line (Model 1a, Fig. 9b) using a typical crystalline basement density ($\rho = 2.67$) for the transparent part of Unit A. This configuration gives a clear divergence between the

Fig. 11. (a) Interpreted entire seismic line R13 (WNW–ESE, Fig. 2 and 6–8) illustrating major unconformities, faults and seismic transparent zones interpreted as salt pillows within the seismic unit A1 (Carbonate-evaporite sequence). The Gondwana and Pan-African unconformities separate the seismo-stratigraphic units A, B and C as defined in Fig. 3. An additional discontinuity separating sub-units A1 and A2 is shown. The top of the crystalline basement is inferred from the gravity and magnetic modeling results. (b) Model 3 (seismic line R13): 2D potential fields models along the line. Note a negative potential field's signature and a good match between modeled and measured curves obtained by considering a low density and magnetic lithology contrasting with surrounding and overlying sediments. Polygons: 1, Unit C; 2, Unit B; 3, sub-Unit A2; 4, sub-Unit A1; 5, Basement. Densities and susceptibilities are given in Table 3.

observed and modeled gravity curves (Fig. 9b). A good fit between the observed and modeled gravity (Fig. 9c) is only obtained when a unique density value of 2.55 g cm^{-1} is allocated to Unit A (Table 3) on the entire line. This strongly suggests that no major lateral lithological change occurs within Unit A along this line L50.



The magnetic modeling shows in the central part of line L50 a considerable divergence between the observed gradient and the modeled curves, except at its northern end (Model 1b, Fig. 9c). This magnetic mismatch contrasts with the excellent fit achieved in gravity modeling and will be discussed later.

- *Model 2* (Fig. 10) is constructed on the NE–SW line L59 in the region of the Dekese well in the southern margin of the Cuvette (Fig. 2), outside the area covered by the aeromagnetic survey (Fig. 8), but characterized by a high gravity gradient (Fig. 6). Anticlinal folds affecting the Unit A, and possibly underlain by salt pillows (see discussion hereafter) are clearly observed on this line (Fig. 10a). In the related model, the fit between observed and modeled gravity curves is achieved with a gradual lateral change in the density of the basement, parallelizing the variation observed in the seismic stacked velocities (Fig. 10b). This change in basement density suggests the presence of a heterogeneous basement or a dense basic magmatic intrusion in the southern part of the profile.
- *Models 3 and 4* (Figs 11 and 12) are located along two WNW–ESE seismic lines, respectively R13 in the Lokonia High and R15 in the Lomami Basin (Figs 2 and 6–8). Line R13 (Fig. 11a) shows in its central part an anticline within the seismo-stratigraphic Unit A, which disrupted the continuity of this unit and reached the U3 unconformity. It disturbed also the overlying Unit B. Smaller anticlines can be seen on both sides of the line, and positive flower structures are rooted on all these anticlines. A similar but less pronounced anticline can be clearly observed on the profile R15 (Fig. 12a) where it affects both Units A and B. Converging reflectors at the top of the structure and toplap geometries highlight the U3 unconformity surface.
  On both lines, Unit B and the underlying Pan-African unconformity appear passively involved in the deformation of the Unit A. On line R-13, deformation locally affects the U3 unconformity while on line R15, this unconformity is undisturbed.
  In order to obtain a good match between the observed and modeled curves for the anticline for these two models (Figs 11b and 12b), a layer of lower density ($\rho = 2.45$–2.47) and susceptibility value ($\mu = 0.2$–0×10^{-6} e.m.u.) has to be introduced above the basement ($\rho = 2.67$; $\mu = 648 \times 10^{-6}$ e.m.u.) and below a layer of relative high density ($\rho = 2.53$ and 2.54) and susceptibility ($\mu = 102 \times 10^{-6}$ e.m.u.). This produces a local inverted trend compared with the expected and normal trend of increasing values of density and susceptibility with depth. The modeled low-density layer ($\rho = 2.45$–2.47) is intermediate between the average density values for sediments used for the Unit A in other models (2.55) and the classical density value of evaporite or salt minerals (2.1–2.3). The low modeled susceptibility values suggest that this low-density layer contains a significant proportion of salt. According to calibrations and correlations, this layer would be equivalent to the carbonate-evaporite sequence found at the bottom of the Mbandaka and Gilson wells (sub-unit A1). The intermediate density and low susceptibility values used to model it are consistent with the idea that this layer is not (or no more) composed of pure salt. It could either have been deposited as a mixture of sediments and impure salt, or as massive salt deposits which are now partly dissolved, or any combination of both possibilities. The overlying, higher density layer would correspond to the clastic sequence found in the same wells (sub-unit A2).
- *Model 5* (Fig. 13) is constructed along the NE-SW seismic line R5 shot on the Congo River, and passing through the Mbandaka well (Figs 2 and 6–8). It displays at its southwestern extremity a poorly defined seismic zone below the U3 unconformity (Fig. 13a). This zone, identified as the 'Kiri High' by Daly *et al.* (1992) is marked by a positive gravity anomaly (Fig. 6). On this line, both Unit A and Unit B are deformed, but these structures are sealed by Unit C above the U3 unconformity. Within the poorly defined seismic zone, weak but relatively well defined sub-parallel reflectors can be seen on more than 2 sTWT (Two Way travel Times) below the upper unconformity.
  To achieve a fair fit between the observed and the modeled profiles (Fig. 13b), a gradual lateral change in basement density along the trend of the profile has to be considered. In such a case, the basement is located 3000 m below the U3 unconformity, i.e. at more than 4000 m depth, corresponding approximately to the bottom of the Mbandaka well (Fig. 13a). This model shows also a gravity high as in model 2 interpreted as reflecting a lateral change in basement density.
  The mismatch between the observed and modeled magnetic values on Model 5 (Fig. 13b) reveals a possible similarity with the deformation style on line L50 (Model 1).

DISCUSSION

Combining seismic, gravity and magnetic 2D models run for the Congo Basin allows individualizing vertical interfaces as well as lateral variations in the subsurface density and magnetic susceptibility of the basement and the sedimentary cover.

Our models show that deformation in the basin is not entirely due to locally uplifted basement as earlier suggested. They indicate that lateral variations of density and magnetic susceptibility values in various compartments of the basement may also in part account for the deformation and potential field signatures in the region. Based on the results of this study, we propose an alternative solution to the basement uplift hypothesis of Daly *et al.* (1992) and provide a possible explanation for the ori-

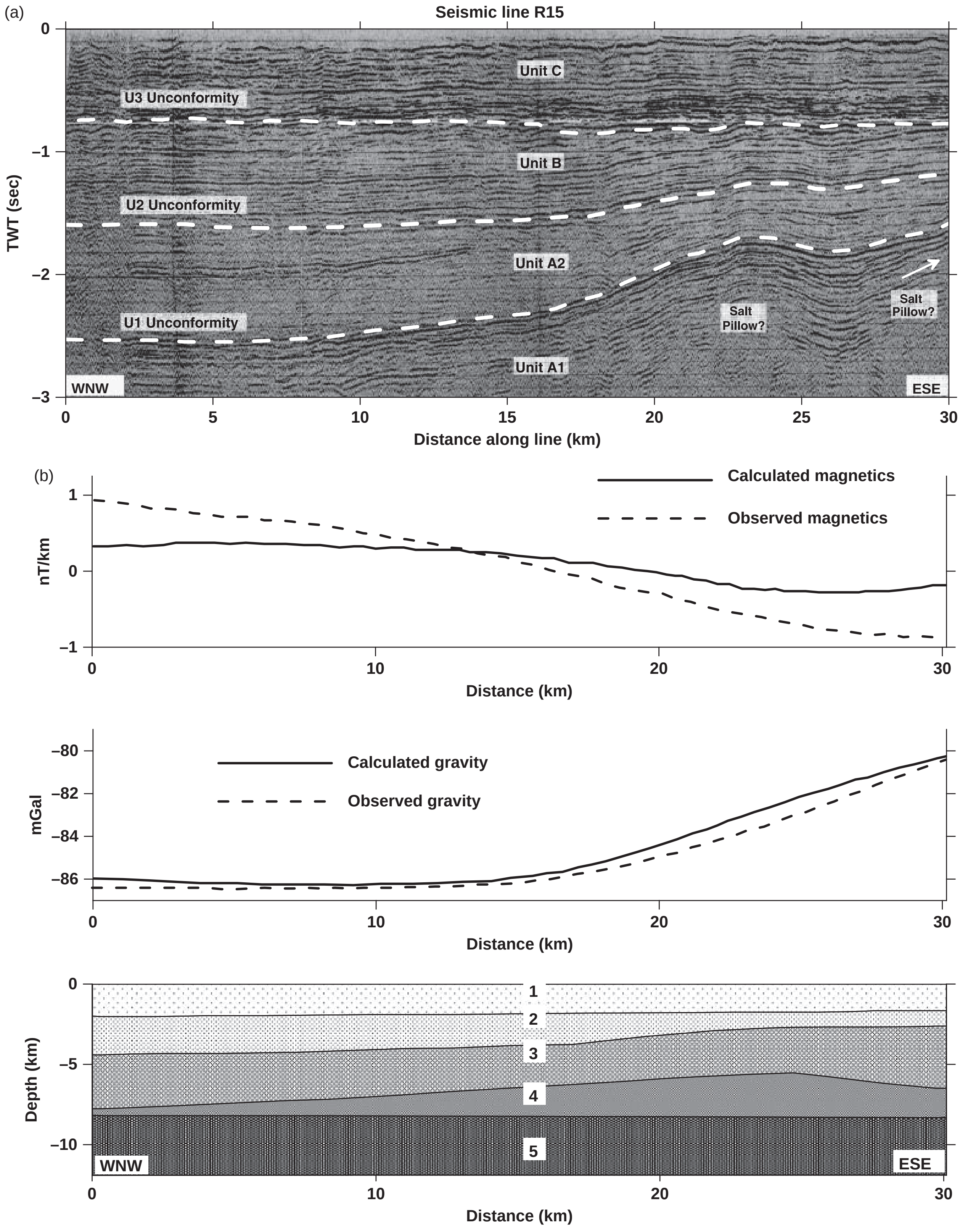
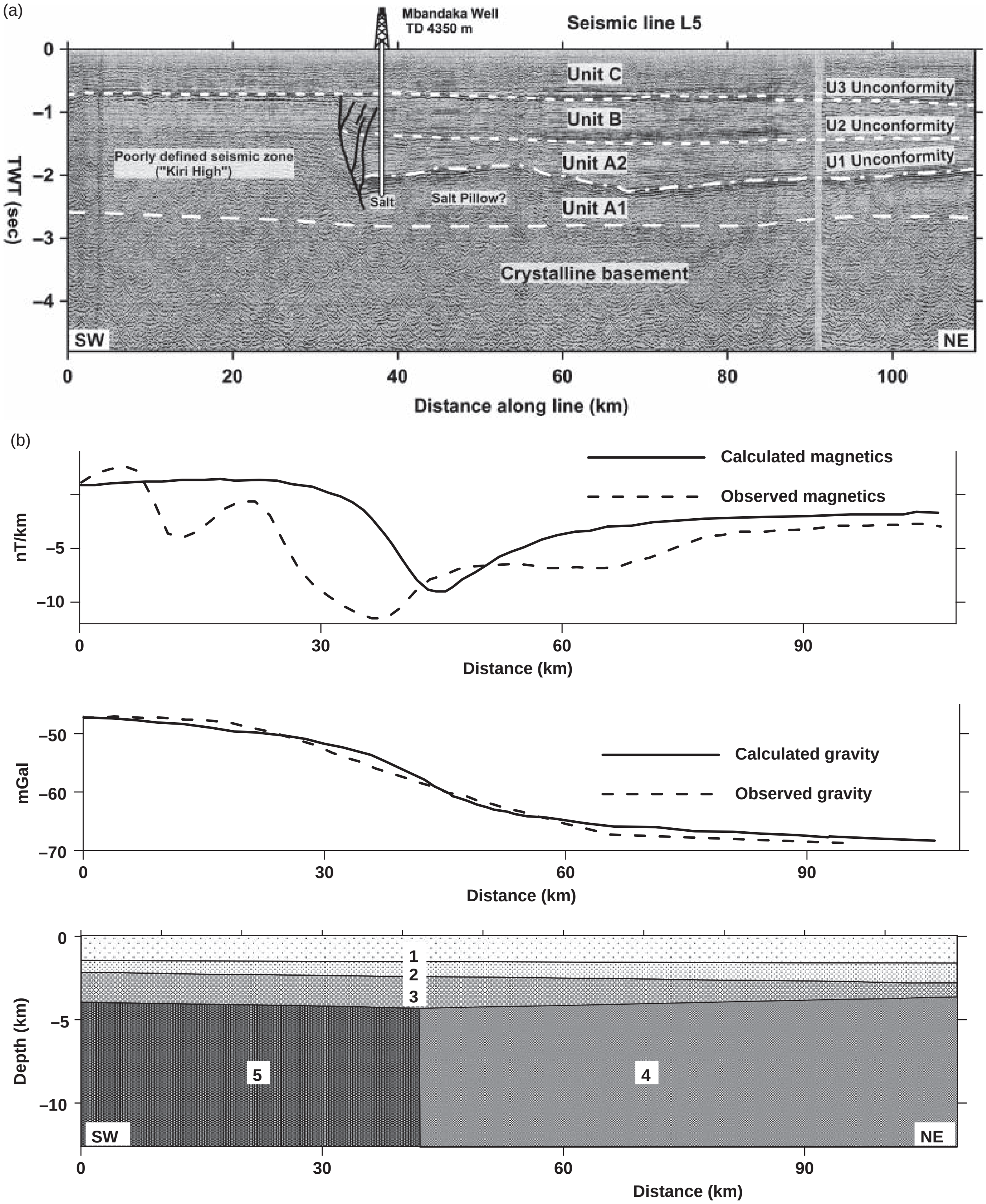


Fig. 12. (a) Interpreted entire seismic line R15 (WNW-ESE, Fig. 2 and 6–8) illustrating major unconformities and possible salt pillows under large anticlines. The Gondwana and Pan-African unconformities separate the seismo-stratigraphic units A, B and C as defined in Fig. 3. An additional discontinuity separating sub-units A1 and A2 is shown. (b) Model 4 (seismic line R15): 2D potential field models along the line showing a good match between modeled and measured curves with a non uplift basement hypothesis. Note a typical magnetic negative signature related to the presence of salt. Polygons: 1, Unit C; 2, Unit B; 3, sub-Unit A2; 4, sub-Unit A1; 5, Basement. Densities and susceptibilities are given in Table 3.

gin of some seismic structures observed in the Congo Basin (i.e. anticlines, seismically transparent zones, and zones of chaotic seismic facies). The proposed alternative does not contradict but rather complements the horst and graben structure of the deep basin as shown by the aeromagnetic grid and the interpretation of the seismic lines.

Evidence for the presence of a deep lying evaporitic formation

In Models 3 and 4 (lines R13 and R15, Fig. 8), we have shown that a local inversion in the normal trend of both density and susceptibility increase with depth is needed to obtain a good match between the observed and modeled curves.



This has been explained by the possible presence at the base of the sedimentary column of a salt-rich low density and susceptibility layer within the carbonate-evaporite sequence (sub-unit A1).

The presence of a deep lying carbonate-evaporite formation in the Congo Basin has been recognized by the Esso Zaire exploration campaign (ECL, 1988), but Daly *et al.* (1992) did not considered the possible contribution of salt for explaining the seismic structures in lines L50 and R5 interpreted to be related to basement uplift. These lines which cross the presumed Kiri High (Figs 2 and 8) are characterized by the presence of poorly defined seismic zones with a transparent seismic facies (Figs 9a and 13a), attributed to an uplifted basement by these authors. For these lines, our 2D gravity and magnetic models 1 and 5 show an important mismatch if we assume high density and susceptibility values to the sub-unit A1 as would be the case with a basement uplift. Instead, a close match between the observed and computed curves in the two models is obtained with crossover or nil zones, i.e., an intermediate salt (evaporite) and sediment density, instead of an uplifted crystalline basement.

These arguments, although not definitive by themselves for the presence of salt in the basal sedimentary series of the Congo Basin, are in line with the suspected development of failed rift basins during the Neoproterozoic within the Congo craton. Moreover restricted marine (lagoon) to sabhka environments with deposition of stromatolitic limestones and evaporites has recently been identified in the adjacent West-Congo, Nguba and Mbuji-Mayi basins.

Evidence for salt movements and collapsed salt structures

In line L50 (Fig. 9a, Model 1), the transparent seismic facies appears as chaotic, while in line R-5 (Fig. 13a, Model 5), it displays weak seismic horizontal reflectors. In this case, these poorly defined seismic zones might correspond to a 'collapsed salt structure' due to the truncation of the salt wall structure, fossilizing past salt movements. Although the poorly defined seismic facies might reflects the limits of the seismic data processing, the characteristics of the U2 unconformity surface and the related toplap seismic facies seen on these lines sustain these conclusions.

In complement to the discussion of models 1-5 above, and in the light of the results of gravity and magnetic modeling, we provide a new interpretation for the structures observed on the corresponding seismic lines L50 and R5, assuming that they are related to the presence of salt in the lower part of the sedimentary succession (sub-unit A1). At the center of line L50 (Fig. 9a), the characteristic seismic facies and deformations observed can be considered as a collapsed structure resulting from salt dissolution. The large anticlinal folds observed in line L59 (Fig. 10a), are interpreted as being rooted by salt pillows. Similarly, the weak transparent seismic facies observed at the base of the anticlines on lines R13 and R15 (Figs 11a and 12a), are considered also as collapsed salt pillows. On the NE side of the Mbandaka well (line 5, Fig. 13a), a gentle anticline could be also rooted by a collapsed salt pillow.

The features observed along these seismic lines typically characterize gravity-driven tectonic deformations of sedimentary formations rich in salt as evidenced in many other basins (Wu *et al.*, 1990; Vendeville & Nilsen, 1995; Vendeville & Rowan, 2002; Zouaghi *et al.*, 2005; Rowan & Vendeville, 2006). In particular, Rowan & Vendeville (2006) modeled the shortening reactivation of existing salt diapirs and related salt-withdrawal minibasins and compared the structures with natural examples. They evidence that the minibasins remain largely undeformed and the diapirs localize the contractional strain. Short diapirs appear to form the core of anticlinal folds and tall diapirs are squeezed. The heterogeneous deformation that results between the minibasins, salt-rooted anticlinal folds and squeezed diapirs is accommodated by variably oriented contractional and even extensional structures. With reference to these examples, we propose that the observed deformations can be due to salt movement caused by compressional basin inversion.

Beyond all structural features mentioned above, geophysical signatures could be used to constrain gravity-driven tectonic features related to the two types of structures as postulated by Prieto (1996). In gravity modeling, such collapsed salt structure corresponds to 'crossover or nil zone' where salt and sediment generating a zero density contrast are observed like in Prieto (1996). Our models 1 and 5 do not require a low density value to match the observed curves for these zones but the corresponding

Fig. 13. (a) Interpreted entire seismic line R5 (NE–SW, running along the Congo River on the western side of the basin, Fig. 2 and 6–8) illustrating the major units and unconformities. The faults forming a flower structure close to the Mbandaka well separate the northeastern part of the profile with well expressed parallel reflectors corresponding to Units A and B, from a poorly defined seismic zone to the southwest. This facies, which Daly *et al.* (1992) relates to a basement uplift (the Kiri High), is interpreted here as being associated to the presence of salt in the sediments. A close examination reflects the presence of well-defined but relatively weak reflectors in continuity with those, better defined of Unit B northeast of the flower structure. Using gravity and magnetic modeling constraints, the top of the crystalline basement is defined under the poorly defined seismic facies in continuity with the northeastern part of the profile. The Mbandaka well stopped at 4350 m deep in massive halite salt. (b) Model 5 (seismic line R5): 2D potential field's models showing a good match between modeled and measured curves obtained with a lateral variation of potential field's properties in the basement. Note a higher frequency and amplitude magnetic anomaly related to the induced magnetization in the zone of poor seismic definition zone. Polygons: 1, Unit C; 2, Unit B; 3, Unit A; 4, Basement 1 (2.67 g cm^{-3}); 5, Basement 2 (2.70 g cm^{-3}). Densities and susceptibilities are given in Table 3.

magnetic models do not fit (Figs 9c and 13b). The observed magnetic curves along these poorly defined seismic zones are characterized by a short wavelength and high amplitude magnetic signal. The short wavelength of the magnetic field anomaly is indicative for a shallow source. The high magnetic amplitude of this anomaly can be explained by the presence of a secondary induced magnetization like for example, a chemical remnant magnetization. Such phenomena can be produced by the truncation of salt walls structure and the filling of dissolved zones by unconsolidated sediments.

Salt tectonics and tectonic inversion

The implication of salt in the tectonic development of the Congo Basin has been inferred to explain the deformation style observed on the seismic profiles (ECL, 1988). It has been further suggested that salt had a passive role in controlling the geometry of sometimes complex zones of structural inversion during compressional tectonics. Salt tectonics in the Congo Basin was proposed by Daly *et al.* (1992) as a consequence of tectonically induced basement uplift. Catuneanu *et al.* (2005) rejected this possibility considering that the contraction and crustal uplift hypothesis was based on an overestimation of the physical strength of the crust, but they did not consider that far-field deformation is generally localized, nor the evidence provided by Guiraud & Bosworth (1997) and Guiraud *et al.* (2005) and the Asian example that far-field stresses are a dominant factor controlling deformation in the cratonic interiors.

The relatively poor processing quality of the seismic sections and their large spacing makes difficult to confirm the structural interpretations of Daly *et al.* (1992). A denser and 3D seismic network would be needed to prove unequivocally the presence of strike-slip and reverse faults in the basin using seismic data alone. However, tectonic fractures are effectively present in the cores of the Dekese well preserved in the archives of the MRAC (Cahen *et al*, 1960). They occur in the Lukuga unit (Couches E-G) that are for a large part inclined at $\sim 30^{\circ}$ from the horizontal, and locally subvertical to overturned. These fractures are numerous, sometimes with a density of several by meter, both reactivating the bedding planes and cutting obliquely to it. They occur as shining surface with nicely impressed slip lines and clear slip sense indicators. Their investigation is currently in progress by the second author (D. Delvaux), and their tectonic character as reverse to strike-slip faults can be confirmed.

The present modeling shows that deformation in this basin is typical of inversion processes related to salt tectonics. The vertical salt movement caused the formation of flexures, anticlines, and contractional faults. Such complex zones can also be responsible for the observed chaotic seismic facies. In function of the regional geodynamic evolution deduced from the analysis and modeling of the seismic lines, these vertical movements within the carbonate-evaporite formation could have been stimulated by the two major tectonic events that affected the African Plate (Pan-African and Permo-Triassic). Although these events were apparently of low intensity in the Congo Basin, the localization of the far-field tectonic stress on existing discontinuities was probably sufficient to have initiated or enhanced the salt movements preferentially above reactivated basement structures.

Early Paleozoic salt movement first started in depocenters like the Dekese depression, and in the present center of the Cuvette, where thick clastic sequences comparable to the Lokoma Group of the Lindi Supergroup overlay the Ituri-type carbonate-evaporite deposits. The topography of the basement, sediment loading and transtensional to compressional regimes related to the Pan-African orogeny influenced vertical salt movement during the Early Paleozoic. Toplap terminations of the seismic reflectors in the upper part of Unit A (Figs 9a and 10a) mark the U2 unconformity and fossilize the truncation of the underlying structure. A second period of salt movement occurred during the Permo-Triassic tectonic reactivation, preferentially in the area where units A and B are the thickest. Such remobilization rejuvenated the Pan-African structures and caused the development of strike-slip faults and thrusts while folds or anticlines are more specifically found in the eastern region. Onlap/toplap geometries of the seismic reflectors within units B and C highlight the U3 unconformity and fossilize the truncation of the Permo-Triassic salt movements (Figs 11a and 12a).

This interpretation can be paralleled with the model of Jackson *et al.* (2003) that infers large-scale salt tectonics during the Lufilian compressional tectonics in the Katangan Copperbelt. After deposition of the Nguba Group, salt destabilization began to form diapirs that have been squeezed during the Lufilian deformation, causing extrusion, megabreccia formation and nape emplacement while the salt progressively disappeared by dissolution. In the Congo Basin, salt dissolution during the long geological history could also be expected, but not completely, as shown by the presence of salt at the base of the Mbandaka well and by the potential field signature evidenced here.

The regional analysis of the structures related to this last deformation event shows a west to east decrease in intensity, corroborating observations made by Tack *et al.* (2001) in the West-Congo fold belt (Fig. 2). To the west, on the prominent Kiri structure (line R5, Fig. 13a), intense faulting is developed and the chaotic seismic facies present directly below the U3 unconformity indicates vertical movement. To the east (line R13, Fig. 11a), salt movement caused the anticlinal deformation of both units A and B. In this case, the top of the anticlinal structures reaches the base of the U3 unconformity, and this creates a negative gravity and magnetic anomaly on the observed profile (Model 3, Fig. 11b). Meanwhile, in the northeastern region (line R15, Fig. 12a), an anticline is principally developed in Unit A. In this case, the low density carbonate-evaporite layer is so deep (6–8 km) that it is not influencing the observed gravity fields.

Heterogeneous and deformable basement

Both Models 2 (line L59) and 5 (line R5) need a laterally heterogeneous basement in order to fit the gravity data. The alignment of the central portions of these lines along a NW trend parallel to the major structures interpreted from the seismic survey (Fig. 2) suggest the presence of NW-SE oriented zone of basement discontinuity beneath the basin. This could well have been originated during the Neoproterozoic failed rifting, itself reactivating the inferred Paleoproterozoic mobile belts that weld together the Archean nuclei of the Congo craton.

CONCLUSIONS

Revision of the stratigraphic, paleogeographic and tectonic constraints allow updating and refining the evolution model of the Congo Basin since the Neoproterozoic.

The Congo Basin evolved largely in an intraplate context, but under the geodynamic influence of tectonic events affecting directly the Congo craton in the Neoproterozoic, its margin in the Neoproterozoic–Paleozoic transition and the margin of Gondwana during the Paleozoic–Mesozoic transition. It has a discontinuous evolution and acquired its present morphology of a 'Cuvette' during the Mesozoic–Cenozoic period. The lower sedimentary sequence at the center of the basin is poorly known, only its upper part is recognized in the Gilson and Mbandaka exploration wells. With reference to adjacent Neoproterozoic basins surrounding the Congo Basin (West-Congo, Ubangi-Lindi, Katanga and Mbuji-Mayi regions), a laguna to sabhka depositional environment in failed rift basins is inferred for this sequence, with stromatolitic limestone and evaporites.

Integration of potential field data as additional constraints in the interpretation of the seismic profiles allows a more precise understanding of the deep sedimentary structures present in the Congo Basin in Central Africa. It highlights the probable importance of salt in the tectonic development of this basin in response to the far-field effects of the Pan-African events that presided to the amalgamation of the Gondwana continent and to the far-field deformation induced by distant the Cape Fold Belt in South Africa during the Permo-Triassic transition as part of the Gondwanide convergent passive margin.

In particular, the seismic interpretation and stratigraphic calibration using the Samba and Mbandaka wells confirm the presence of two prominent regional unconformities (U2 and U3) representing the Pan-African and Gondwanide events that separate the sedimentary succession of the Congo Basin into 3 major seismo-stratigraphic units (A, B and C), corresponding broadly to the (Late) Neoproterozoic, Paleozoic and Meso-Cenozoic. The careful re-examination of the seismic profiles together with integration of gravity and magnetic modeling suggest the locally significant presence of salt within the lower part of the Neoproterozoic sequence (carbonate-evaporite formation, sub-unit A1). The deformations observed along the seismic lines can be locally related to vertical movement of the Neoproterozoic salt, triggered by the Pan-African and Gondwanide tectonic events.

As a consequence, deformations within the Congo Basin can, at least locally, be explained without invoking only the previous hypothesis of uplifted basement (Daly *et al.*, 1992). For instance, the narrow WNW–ESE trending Kiri High has been interpreted as an uplifted basement based on the assumption that the poorly defined seismic facies corresponded to the crystalline basement. Using the potential field constraints, we have shown that it can be more satisfactorily explained by the presence of salt-rich formations. The chaotic aspect of the seismic facies and the related tectonic structures are explained by the mobilization of the carbonate-evaporite formation during the Pan-African and Permo-Triassic reactivations. We are also aware that with this work, we reached the limit of the interpretation of the seismic profiles in their present form and that they certainly need a modern reprocessing.

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