Evidence of a large upper-Cretaceous depocentre across the Continent-Ocean boundary of the Congo-Angola basin. Implications for palaeo-drainage and potential ultra-deep source rocks

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The analysis of 2D deep-seismic-reflection profiles across the slope and abyssal plain of the Angola oceanic basin reveals the existence of a significant and formerly unknown depocentre beneath the giant Cenozoic Congo deep-sea fan, between 7000 m and 9000 m depth, deposited directly onto the Aptian oceanic crust. The unit, which is up to 2.5 km thick and extends for more than 200 km basinwards of the Continent-Ocean boundary, is probably aged Albian–Turonian. Its radial fan-shaped depocentre is cen-tred on the present-day Congo River outlet and contains at least 0.2 Mio km^3 of sediments. These observations and the results from flexural modelling indicate that (1) the location of the Congo River's outlet has remained fairly stable since the Late Cretaceous, and (2) the basal unit was indeed sourced by a palaeo-Congo River probably located nearby the present-day one. Thus, the Atlantic sedimentary system related to the exoreism of the Congo River is much older than previously thought. Thermal modelling indicates that the maturation history of this upper-Cretaceous deposits is highly influenced by the interaction between the initial high heat flow of the young oceanic crust and further increase in sediment supply due to the progradation of the overlying Tertiary deep-sea fan during the Miocene. Hence, despite low present-day heat-flow values, should the unit have source rock potential, its basal section may be currently generating hydrocarbons.

All in all, the results from our models also suggest that the interplay between an initially high heat flow and the further high sediment supply in areas of major river input, may be a key factor for the thermal maturation of potential source rocks deposited onto a present-day "cold" oceanic crust.

1. Introduction

The architecture and stratigraphy of the Congo-Angola continental margin are fairly well constrained mostly due to intensive hydrocarbon exploration (e.g. Emery et al., 1975; Karner and Driscoll, 1999; Marton et al., 2000; Meyers et al., 1996; Teisserenc and Villemin, 1989). However, the lack of boreholes on the abyssal plain of the Angola oceanic basin has limited our understanding of the distal units deposited beyond the Continent-Ocean boundary (COB). Only relatively recently, the extensive deep-seismic-reflection dataset from the ZaiAngo project allowed us to decipher the entire extension of the Tertiary Congo deep-sea fan on the abyssal plain of the basin and study its interaction with the evolution of the margin (Anka and Séranne, 2004; Anka et al., 2009). Nevertheless, the older basal-most sedimentary units deposited directly on the oceanic crust were still mostly unknown, and therefore our knowledge of the post-rift history of the oceanic basin remained incomplete.

Upper-Cretaceous post-rift sedimentation beyond the continent-ocean boundary has frequently been thought as mainly thin hemipelagic deposits with little or no sand deposition (Evans, 2003). The Kouilou-Niari River, a minor coastal system to the north of present-day Congo River (Fig. 1a), has been considered as the only source of clastics into this basin during this period (Uenzelmann-Neben, 1998). In contrast, important upper-Cretaceous terrigenous deposits have been identified to the north and south of the basin, mainly sourced by the Ogoué and Kwanza Rivers respectively (Goudie, 2005; Lucazeau et al., 2003).

It is currently widely accepted that the main terrigenous input into the Angola oceanic basin started during the Oligocene with the turbidite deposits associated with the Congo River (Anka and Séranne, 2004; Brice et al., 1982; Uchupi, 1992). This Tertiary clastic sedimentation replaced the previous carbonate-dominated deposits

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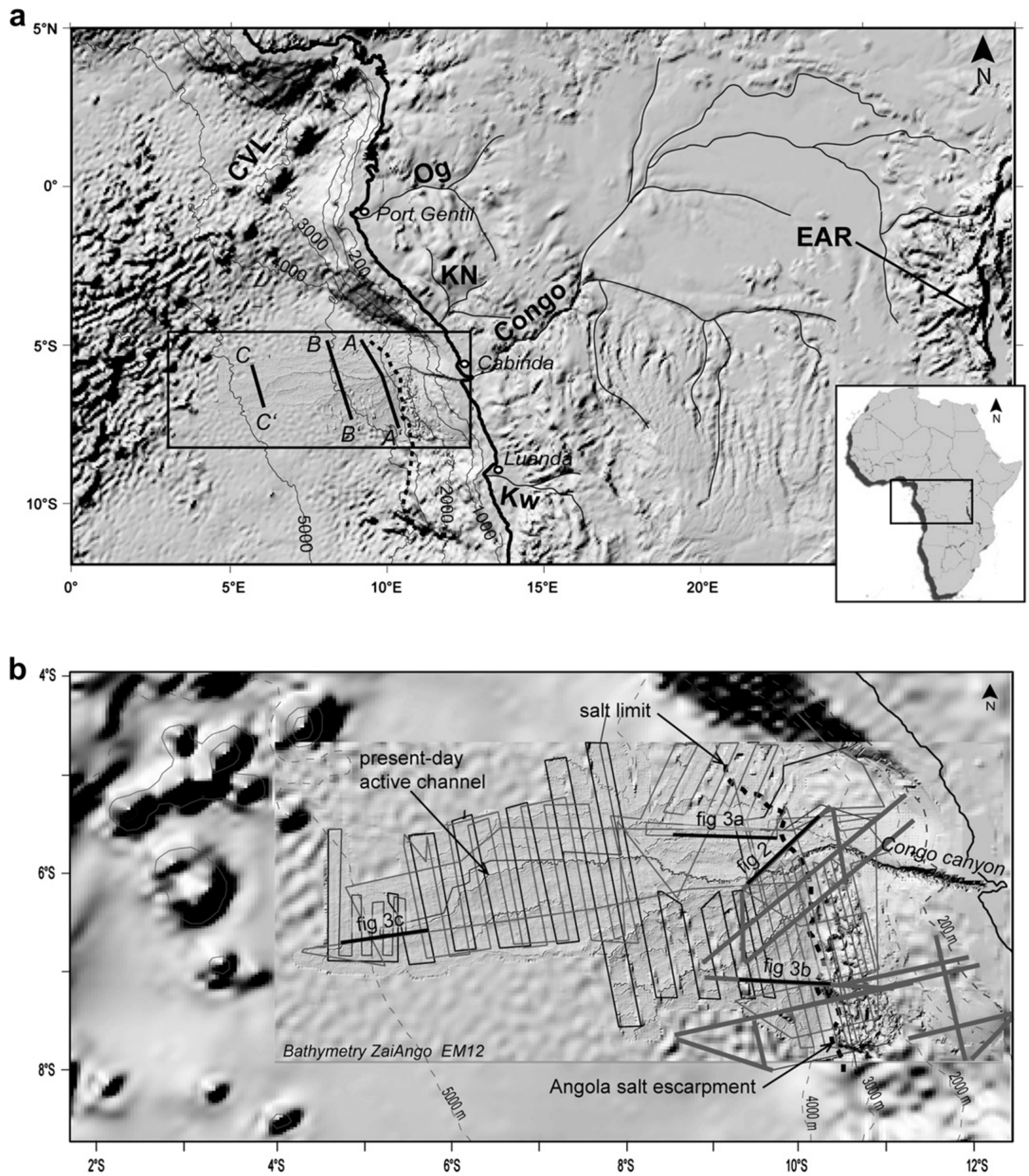

Fig. 1. a. Congo-Angola oceanic basin depicting the Congo River – submarine canyon-deep-sea fan system and majors Atlantic draining rivers. CVL: Cameroon volcanic line, EAR: East Africa Rift, KN: Kouiloi-Niari Rivers, Kw: Kwanza River, Og: Ogoué River. (Rectangle represents location of 1b and AA′, BB′, CC′ refer to the strike sections shown in Fig. 4.). b. ZaiAngo's bathymetry EM12 showing the major physiographic features of the oceanic basin. The black-dashed line represents the limit of the salt basin which is located near the COB. 2D Seismic grid analysed in this study: ZaiAngo SMT (thick grey lines), ZaiAngo HR 6-channels (fine black lines), ZaiAngo HR 96-channels (fine grey lines).

that built-up the Cretaceous shelf. Several hypothesis have been put forward in order to explain the apparent absence of important terrigenous supply to the Angola oceanic basin during the Late Cretaceous: (1) the presence of a rift shoulder acting as a western barrier for the Congo River that could have forced the river to flow eastwards into the Indian Ocean, across the present-day location of the East African rift (Stankiewicz and de Wit, 2006), (2) the interior drainage basin possibly draining through northern Gabon during the Late Cretaceous, until the rift shoulder was sufficiently eroded to allow the Congo River to capture the drainage system in Angola in the Tertiary (Nibbelink, 2002), (3) a depocentre switch from Ogoué and Kwanza to Congo at the end of the Cretaceous due to the capture of the endoeric Congo system (Leturmy et al., 2003; Lucazeau et al., 2003).

In this paper we present the results from analysing the ZaiAngo deep-seismic-reflection profiles, which allowed us to identify a formerly unknown basal units deposited onto the oceanic crust. This has lead to (1) the re-interpretation of the post-rift history of sediment supply in the basin, (2) a reconsideration of the stability of the Congo River as a long-term sediment supplier to the South Atlantic, and (3) the evaluation of potential hydrocarbon source rocks beneath the Tertiary Congo fan and basinwards of the COB.

2. Geologic setting

The Angola oceanic basin is located offshore the Congo-Angola passive margin and resulted from the opening of the south Atlantic following the separation of Africa and South America. The continental rifting started during Neocomian times, around 144–140 Ma and ended during late Barremian to early Aptian (Guiraud and Maurin, 1992; Karner and Driscoll, 1999; Nürnberg and Müller, 1991). The most important physiographic element currently present in the basin is the Congo canyon and deep-sea fan system, which contains at least 0.7 Mkm^3 of Tertiary sediments transported by the Congo River, representing one of the largest sedimentary system in the south Atlantic (Anka and Séranne, 2004; Droz et al., 2003). There is a present-day direct connection between the river's continental drainage area (the 2nd largest in the world) and the deep basin through the impressively incised Congo submarine canyon (Fig. 1a).

Following the rifting, restricted-marine conditions favoured the deposition of thick Aptian evaporites responsible for the prominent salt tectonics that characterises the margin. Due to gravity sliding of the post-rift sequences over this decollement level, the COB is probably located landwards of the actual salt limit (Fig. 1a, b) (Jackson and Hudec, 2005; Marton et al., 2000; Moulin et al., 2005).

Three main mega-sequences are classically recognised within the post-rift deposits of the margin: (1) from Albian to Late Cretaceous: an aggradational carbonate shelf followed by an increasing sedimentation dominated by marls and clays (Lavier et al., 2001), (2) from Late Cretaceous to Eocene: a ramp-shaped mixed (carbonate/siliciclastic) platform, containing the source rock for the overlying hydrocarbon-bearing sands, that pinches out seaward into condensed sections (Anderson et al., 2000), (3) from Oligocene to Present: a wide progradational clastic wedge representing the Congo Cenozoic deep-sea fan (Anka and Séranne, 2004; Anka et al. 2009).

During the late Eocene and early Oligocene there is a dramatic increase in clastic sedimentation and a wide-spread stratigraphic reorganization from mainly aggradational to progradational (Séranne, 1999) as well as a wide-spread regional erosional event on the slope, platform, and the coastal range whose origin, whether tectonics or climate-driven, is still matter of controversy (Lavier et al., 2001; Lunde et al., 1992; Séranne et al., 1992).

3. Data and methodology

This work is based on the analysis of an extensive 2D seismic-reflection dataset from the ZaiAngo project. The seismic grid was composed of 2 surveys: *ZaiAngo SMT* and *ZaiAngo HR* consisting of prestack Kirchoff time-migrated seismic profiles, which image the oceanic basement at more than 8 s TWT. Altogether they represent more than 20,000 km of seismic lines, interwoven on a grid spacing raging from 6 to 25 km, covering an area of about 200,000 km^2 from the slope to the abyssal plain (Fig. 1b).

3.1. Seismic ZaiAngo SMT

It consists of 17 deep-penetration multi-channel seismic-reflection profiles, equivalent to 3180 km of lines, acquired during March–April 2000 with the R/V Le Nadir (Ifremer) using a single-bubble air-gun array and a 4.5 km long 360-channel digital streamer. The conventional data-processing sequence, carried out by the Marine Geosciences Department of Ifremer using the Geovecteur Software, mainly included: spherical divergence correction, anti-multiple, depth-dependent dynamic equalization, external mute, F–K multiple attenuation, internal mute to attenuate the water bottom multiples, velocity analyses every 2.5 km, stack, time-dependent filtering, dynamic equalization, and time migration using a Kirchoff algorithm (see Construcci et al., 2004; Moulin et al., 2005 for more details on data acquisition and processing).

3.2. Seismic ZaiAngo HR

It contains almost 19,000 km of high-resolution seismic profiles acquired during two cruises (ZaiAngo 1 & 2) with the R.V. L'Atalante (Ifremer) from September to November 1998. Two systems of seismic acquisition, both using high-resolution sources composed of small volume gas-injection guns operated at shallow depth, were operated. The first system had a source consisting of two gas-injection guns, shooting at a rate of 11 s, and the data were collected on a six-channel, 300-m-long streamer at a sampling rate of 500 Hz. The second had a source in an array of six gas-injection guns, shooting at a rate of 10 s, and the data were collected on a 96-channel, 2400-m-long streamer towed at 3 m below the sea surface. (Savoye et al., 2000; Droz et al., 2003). The data were both processed by the staff of Ifremer using the PROMAX software and consisted mainly on: geometry and dynamic correction, F–K and bandpass filter, stack, migration, mute, and gain (Droz et al., 2003; Tania Marsett, pers. comm.)

The interpretation was carried out using the seismic interpretation software Sismage Research® developed by the oil company Total following a conventional 2D interpretation methodology of delimitation of seismic reflectors and markers, unconformities, and onlap/downlap surfaces, followed by the construction of surface-depth and isopach maps and well-seismic ties. We focused our analysis on the basal seismic units deposited basinwards of the salt limit, which is located roughly near the COB, as the seismic dataset allowed for the first time to image these deep and distal areas of the basin. Due to the absence of wells in the abyssal plain, the ages of the seismic reflectors were determined by long-distance correlation to well tops located on the northern upper-slope, landwards of the COB.

Seven surfaces were built from the TWT interpreted horizons: ocean crust, intra C1, top of C1, base Oligocene, Mid. Miocene, base Pliocene, and seafloor. The surfaces were then converted from TWT (s) into depth (m) using interval velocities. This allowed us to analyse variations on the sediment budget in space and time. The average thickness was derived by dividing the bulk deposited volume by the area where the unit was identified. The sedimentation rates were then calculated by dividing the average thickness by the duration of the deposition interval. We are aware that these are minimum possible values as only compacted thickness values were used in the calculations. Subsequently, we modelled the possible peripheral-flexural deformation caused by the sedimentary loads associated to the basal distal units as well as the age-equivalent units located on the shelf and proximal areas. This allowed us to predict the likely interaction between these deposits and the on-shore coastal drainage in order to evaluate the stability of the Congo River's outlet through time and its potential as feeder of the basal oceanic deposits.

Additionally, we investigated the hydrocarbon generation potential of the units identified beneath the giant Congo deep-sea fan and beyond the COB by modelling their thermal evolution and maturation history using IES's commercial software Petromod™.

4. Seismic interpretation of distal-basal units

Fig. 2 shows a regional seismic profile depicting the main seismic units identified both landwards and basinwards of the salt limit. The boundary between the seismic basement (OC) and the overlying sedimentary cover is visualised by a strong contrast in acoustic impedance. OC represents the oceanic crust, whose age is still uncertain since no clear magnetic anomalies have been found on this area of the South Atlantic. Published ages range from Barremian (*i.e.* Brice et al., 1982; Marton et al., 2000) up to close to Chron M0 – 125 Ma – (Aptian) (Guiraud and Maurin, 1992; Karner and Driscoll, 1999; Nürnberg and Müller, 1991; Teisserenc and Villemin, 1989). Hence, sediments deposited above OC are, at oldest, Aptian/Albian.

In general, all the units thicken basinwards of the salt limit into the oceanic domain, in particular the prograding wedge of the Oligo-Miocene fan (Fig. 2). Even more interesting is the presence of a thick basal unit "C1" found at about 7000–9000 m, which is overlying unconformably the oceanic crust. C1 is top-bounded by

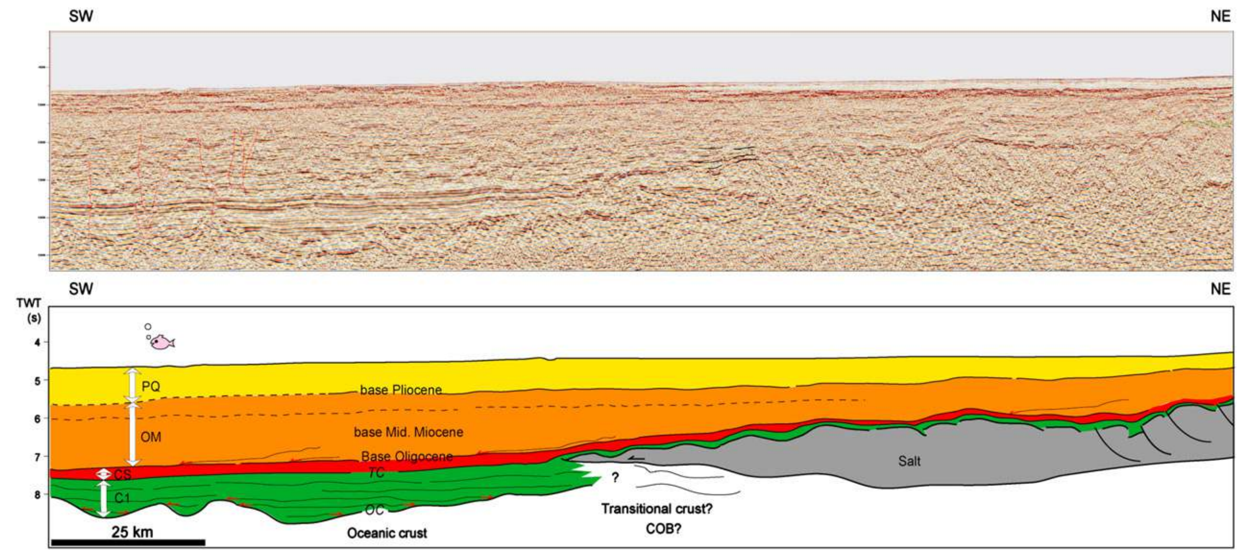

Fig. 2. Regional seismic profile and interpretation line drawing showing the main seismic units identified at the continent and oceanic domain. PQ: Plio-Quaternary fan, OM: Oligo-Miocene fan, CS: condensed section, C1 basal oceanic unit.

a conspicuous double seismic marker "TC" that can be traced almost throughout the entire basin.

At the base of the present-day slope, that is just off the salt limit, C1 presents a wedged external geometry, composed of parallel, relatively strong internal reflections, which are onlapping and filling depressions on the oceanic crust (Fig. 3a,b). In contrast, on the outermost areas of the abyssal plain C1 external geometry is a thin-sheet draping the oceanic crust (Fig. 3c). Not only the external, but also the internal characteristics of the unit change considerably basinwards. As it varies from a wedge-shaped to a draping sheet, its thickness decreases almost tenfold from the base of the slope to the outermost abyssal plain. Simultaneous to this thinning, the unit's internal reflections turn into a rather transparent acoustic facies in this direction (Fig. 3a–c).

Based on their seismic characters the most-distal seismic facies can be interpreted as homogeneous, low-energy deep-marine pelagic deposits, while the relative amplitude-increase landwards suggests an increase in sand-bearing facies in this direction

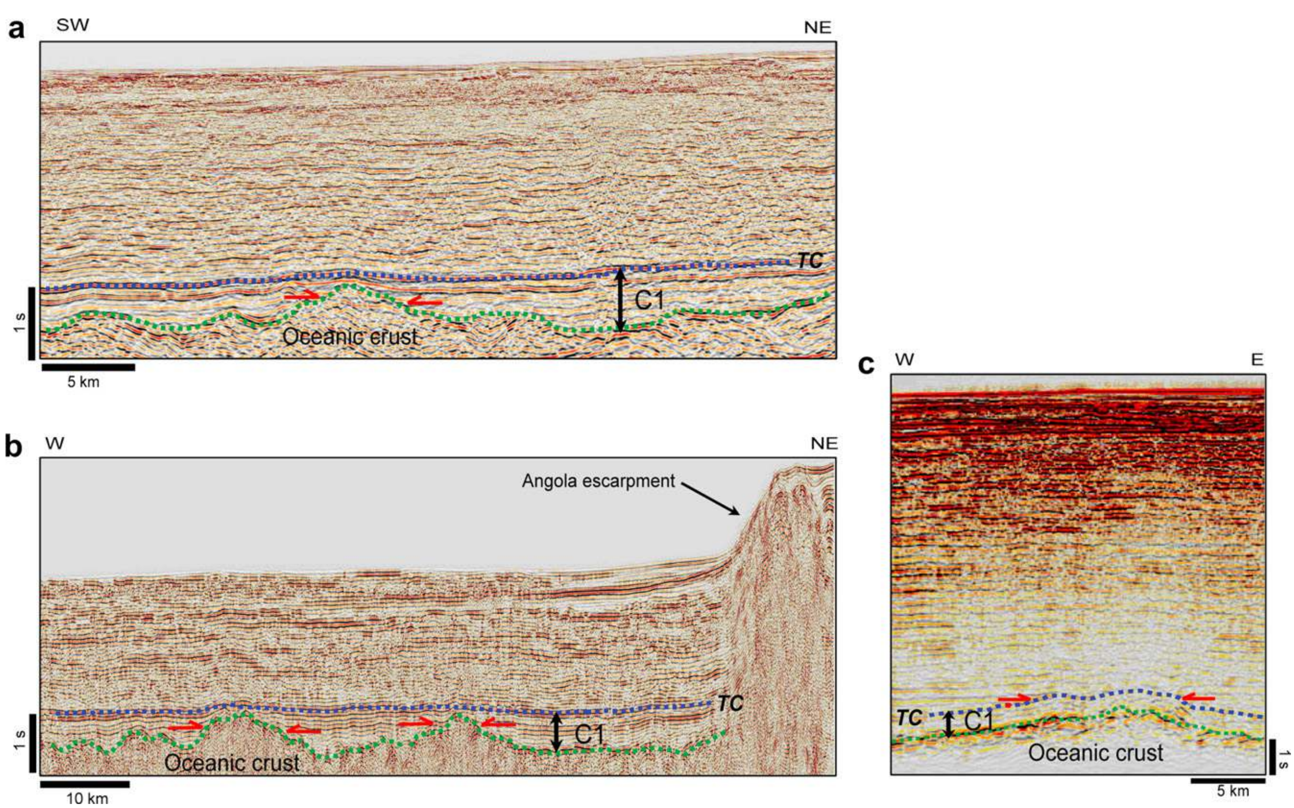

Fig. 3. Seismic expression of the basal oceanic unit C1. a) At the base of the northern slope, b) at the southern slope, c) in the outermost areas of the abyssal plain. TC: seismic marker top of C1 (location shown in Fig. 1b).

(Sangree and Widmier, 1979). Altogether, the above described variations indicate a landward modification on the depositional process operating during C1 deposition.

When tied to wells on the northern slope, the top of C1 – reflector "TC" – corresponds to the end of Turonian, which has been reported as a period of a maximum deepening of the shelf (Anderson et al., 2000). Therefore, assuming that the oceanic crust is Aptian, C1 should comprise – at oldest – the Albian–Turonian sedimentation span, thus representing the distal equivalent of the carbonate-ramped shelf widely described in the literature (*i.e.* Anderson et al., 2000; Lavier et al., 2001; Massala, 1993). On the other hand, a thin post-Turonian unit "CS", which is overlying C1 and underlying the Oligo-Miocene fan, thins basinwards until it is no longer recognizable on the most-distal areas of the basin (Anka et al., 2009). Thus, reflector "TC", which is the top of C1 at the base of the slope, represents either a hiatus or a condensed section on the abyssal plain.

Although the interpretation of C1's age remains somewhat speculative due to the lack of wells in the distal areas of the basin, the existence of this thick basal unit overlying the oceanic crust, and beneath the Congo Cenozoic sedimentary wedge, has not – to the best of our knowledge – been shown before, and rules out the wide-spread hypothesis that the main Albian–upper-Cretaceous depocentres on the Gulf of Guinea were located to the north and south, but not in the Congo-Angola basin.

5. Possible interaction between the Cretaceous deposits and the on-shore coastal drainage

It has been shown that the load of large submarine sedimentary units may produce on-shore peripheral flexural uplifts, which can lead to modifications on the pattern of adjacent coastal drainage, e.g. the Indus fan (Whiting et al., 1994) and the Amazon fan (Driscoll and Karner, 1994). Consequently, in view of the newly identified unit C1, we have modelled the flexural deformation caused by the Cretaceous deposits in order to analyse its possible control on the stability of the Congo River's outlet through time.

These peripheral flexural uplifts result from the regional compensation of a downward deflection that takes place on a rigid lithosphere under the action the surface loads (*i.e.* Driscoll and Karner, 1994; Lavier et al., 2000; Lucazeau et al., 2003; Watts, 1982; Watts and Torné, 1992; Whiting et al., 1994). In this sense, the transversal margin-paralleled sections across the rise and the abyssal plain of the Congo-Angola basin show a similar downward deformation on the oceanic crust underlying C1 deposits, which decreases basinwards as C1 thins in this direction, clearly suggesting that the load of C1 is the origin of the deflection. (Fig. 4). Likewise, the Cretaceous depocentres linked to the Ogoué and Kwanza Rivers to the north and south of the basin are regionally as large as C1 depocentre and an important flexural deformation have

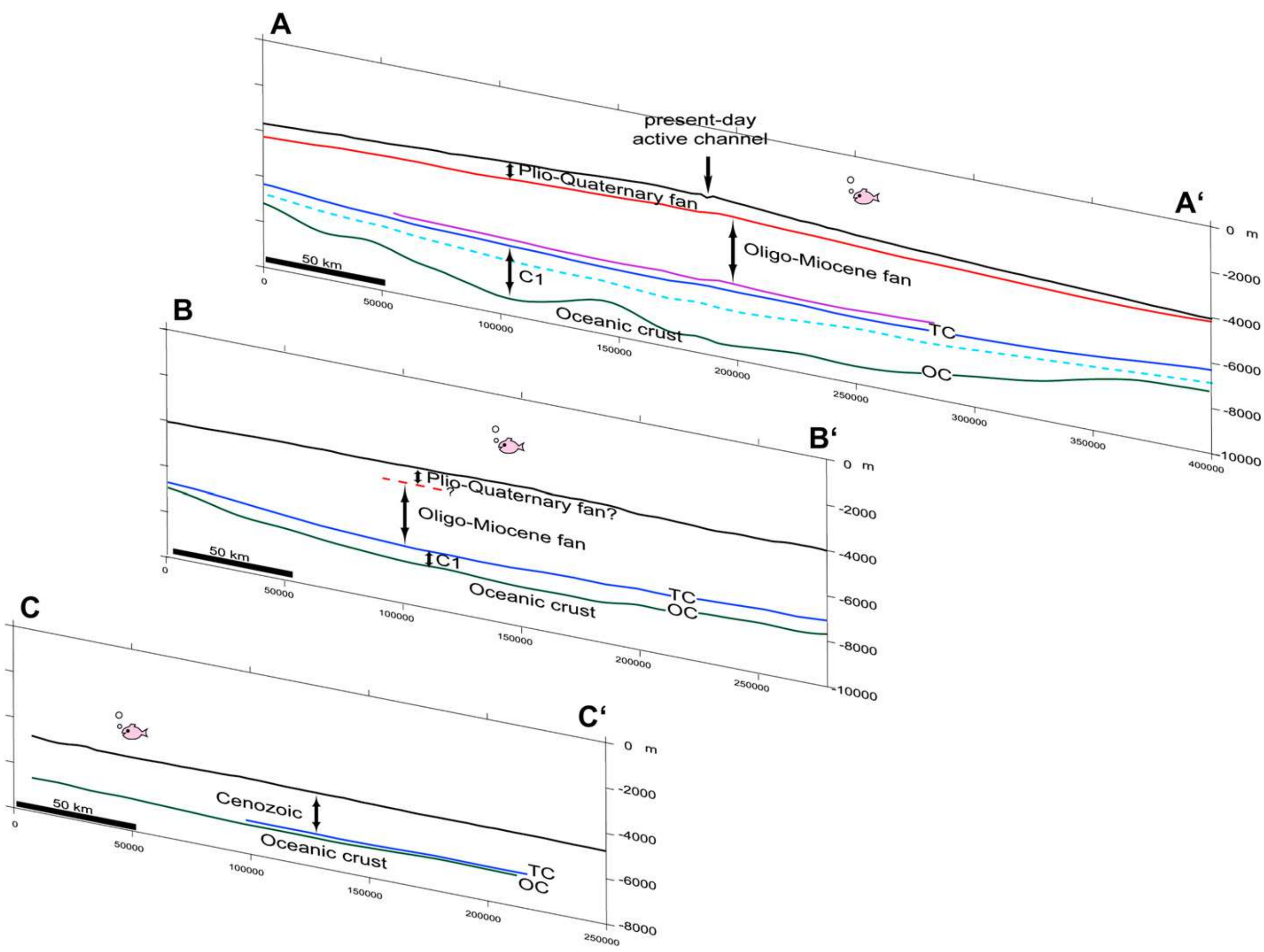

Fig. 4. Margin-paralleled transversal sections showing the downward deflection of the oceanic crust beneath C1 deposits. As C1 thins basinwards, the deformation decreaces (location shown in Fig. 1a).

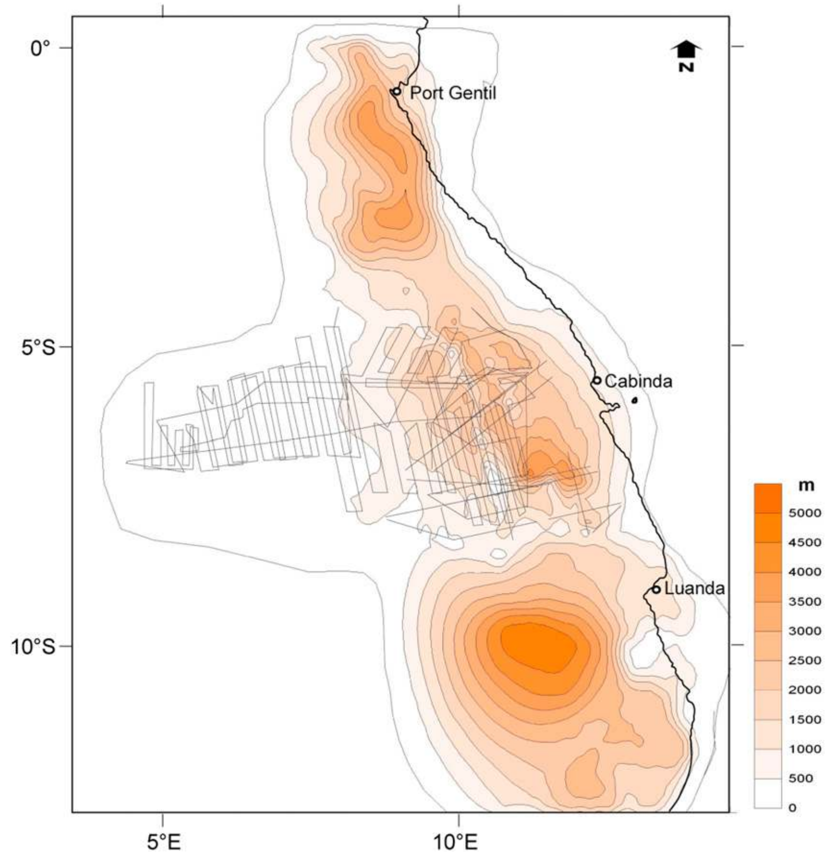

Fig. 5. Isopach map of off-shore and on-shore Cretaceous deposits in Gabon, Congo, Angola and Kwanza basins (compilation from Massala, 1993; Lucazeau et al., 2003, and this study).

been associated to their loads (Lucazeau et al., 2003). As we aim to analyse the long-term stability of the Congo river's outlet, after C1 deposition and previous to the tertiary fan onset, we need to consider the total cumulative flexural deformation caused by all the Cretaceous loads, and not only C1. Hence, the loads in our model include not only C1, but also the Ogoué and Kwanza cretaceous depocenters, as well as the Cretaceous shelf deposits that are age-equivalent to C1 (Massala, 1993) (Fig. 5). By doing so, we also minimize unrealistic numerical effects, as uplifts on the oceanic domain contiguous to C1 depocentre, resulting from considering C1 as an isolated load.

We used a finite-element elastic thin-plate model, which assumes that the lithosphere behaves as an elastic plate floating on a fluid (Bodine et al., 1981). One of the main input values of is the effective elastic thickness of the lithosphere "Te" at the time of loading. In the case of an oceanic lithosphere, Te is mainly constraint by the thermal structure of the lithosphere, and thus by its age (*i.e.* Caldwell and Turcotte, 1979; McNutt and Menard, 1982; Watts et al., 1980). Depending on the author, Te values will fall either within the depths of the 300 °C and 600 °C isotherms (Bodine et al., 1981; Watts, 1978) or at the depth of the 450 °C isotherm (Burov and Diament, 1995). We assumed that the oceanic crust in this part of the margin is Aptian (119–113 My) and that the whole sedimentary load has been entirely deposited by the end of Turonian. Thus the "thermal" age of the oceanic lithosphere at the time of loading would be 16–22 My and the possible Te values under these conditions are shown in Table 1. The flexural deformation was then modelled for three values of Te within the predicted range: Te = 10, 15, and 20 km. The other input variables used in the model are mostly related to the physical characteristics of both the effective load and the lithosphere (Table 2).

The results from the simulations indicate that a flexural downward deflection of 1200–1600 m (depending on Te's value) could have taken place beneath C1 depocentre (Fig. 6a–c). Likewise, the regional propagation of this effect would have set the Cretaceous shelf to a flexural subsidence of about 600 m in the area of the Congo basin, which could correlate with the episode of maximum

Table 1
Average values of the effective elastic thickness "Te" for an oceanic lithosphere aged about 16–22 My at the time of C1 "instantaneous" loading.

Compilation	Te (km) at the time of loading		
	Isotherm 300 °C	Isotherm 450 °C	Isotherm 600 °C
Burov and Diament (1995)	10–13	12–14	20–25
Bodine et al. (1981)	9–11	14–16	17–22

Table 2
Input values used on the numerical modelling of the flexural deformation caused by the Cretaceous load.

Variable	Description	
ρ_a	Density of the asthenosphere	3150 kg/m^3
ρ_{fill} ou ρ_w	Density of the water	1020 kg/m^3
ρ_{sed}	Density of the sediments	2440 kg/m^3
$\Delta\rho_2$	Effective density or «buoyancy» ($\rho_a - \rho_{fill}$)	2130 kg/m^3
$\Delta\rho_1$	Effective density of the load ($\rho_{sed} - \rho_w$)	1420 kg/m^3
Te	Effective Elastic Thickness	20–30–40 km
E	Young's module	5×10^{10} Pa
ν	Poisson's coefficient	0.3
g	Acceleration of gravity	9.81 m/s^2

deepening registered in the shelf by the end of the Turonian (Anderson et al., 2000). On the other hand, the model also predicts a semi-continuous on-shore flexural uplift of about 40–50 m on the Congo-Angola margin and larger than 100 m to the north, around the Ogoué River. Although these uplift values do not explain a present-day coastal high that is one-order of magnitude higher, the flexural-uplift stripe presents a series of transversal minimum-uplift areas, which coincide with the present-day major river valleys (Fig. 7a). It might be likely that palaeo-rivers draining into the Atlantic were preferentially located across these axial lows, delivering clastics at these selected points along the margin. Interesting is the fact that the Present-day Congo river crosses ones of these areas. In the following section we will discuss the possible implications of these results on the role of the Congo River as a long-term sediment supplier into the Atlantic.

6. Discussion

6.1. Implications on palaeo-drainage

The described internal and external variations on the seismic character of C1 become more geologically significant when analysed in conjunction with the unit's thickness distribution. The isopach map of C1 depicts a wide radial fan-shaped depocentre whose maximum thickness, up to 2500 m, is centred on the present Congo River's outlet – submarine canyon axis (Fig. 7a). In contrast, the lateral age-equivalent deposits, which represent the aggrading ramp-profiled shelf of Pinda and Iabe Groups (Massala, 1993; Anderson et al., 2000; Lavier et al., 2001), are elongated and mostly parallel to the margin with an orientation predominantly NW-SE, *quasi*-perpendicular to the orientation C1 depocentre (Fig. 5). The main depocentre, more than 2500 m thick, is located to the south-east of the submarine canyon, and thus eccentric with respect to the river's outlet-canyon axis.

The minimum estimated volume of C1 is significantly smaller than the overlying giant Tertiary fan: about 0.2 Mio km^3 *vs.* 0.7 Mio km^3 respectively (Fig. 7b). Nevertheless, the average deposition rates on the lower slope are fairly similar, and quite high, for both time intervals: about 75–80 m/Ma. These results have an unexpected implication: the sediment supply on this domain, and thus the sediment-transport mechanism, was as efficient during Late Cretaceous as during the Oligocene-Miocene. Therefore, a high-energy mechanism similar to the action of the turbidity currents responsible of the Oligo-Miocene fan deposition must have been operating at the time of C1 deposition. Such a sediment-transport dynamics would not only explain the landward sand-content increase interpreted from seismic profiles, but also the internal onlaps observed in C1 proximal deposits as turbidite currents generally deposit sediments onlapping the pre-existent substratum. In contrast, C1's distal deposits on the abyssal plain present three-fold lower deposition rates, which is consistent with the hemi-pelagic nature interpreted for this deposits from the seismic data.

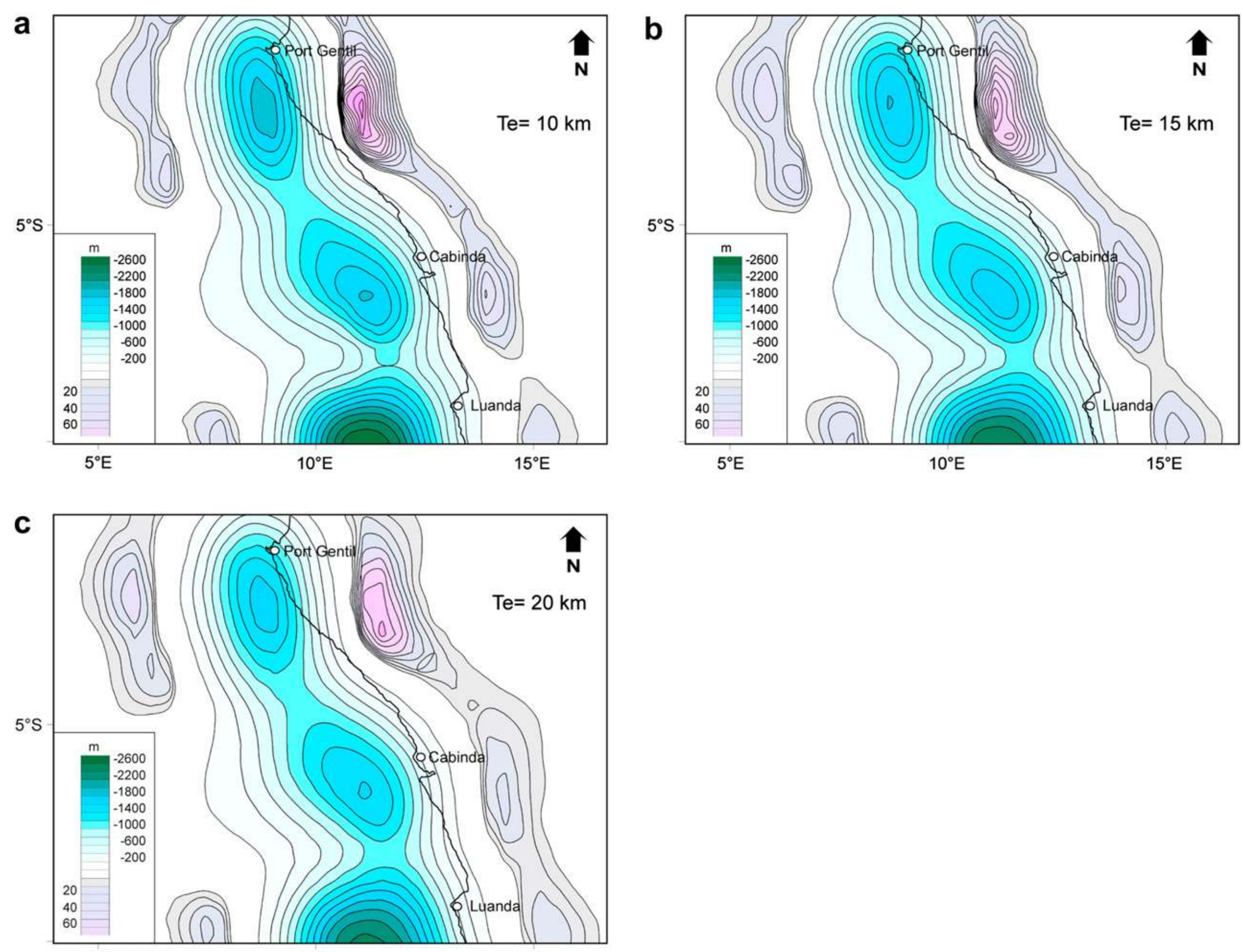

Fig. 6. Modelled flexural deformation probably caused by the load of Cretaceous deposits, including the basal unit C1. Simulations for an effective elastic thickness of a) Te = 10 km, b) Te = 15 km, c) Te = 20 km. (Negative values: downward deflection. Positive values: peripheral flexural uplift.)

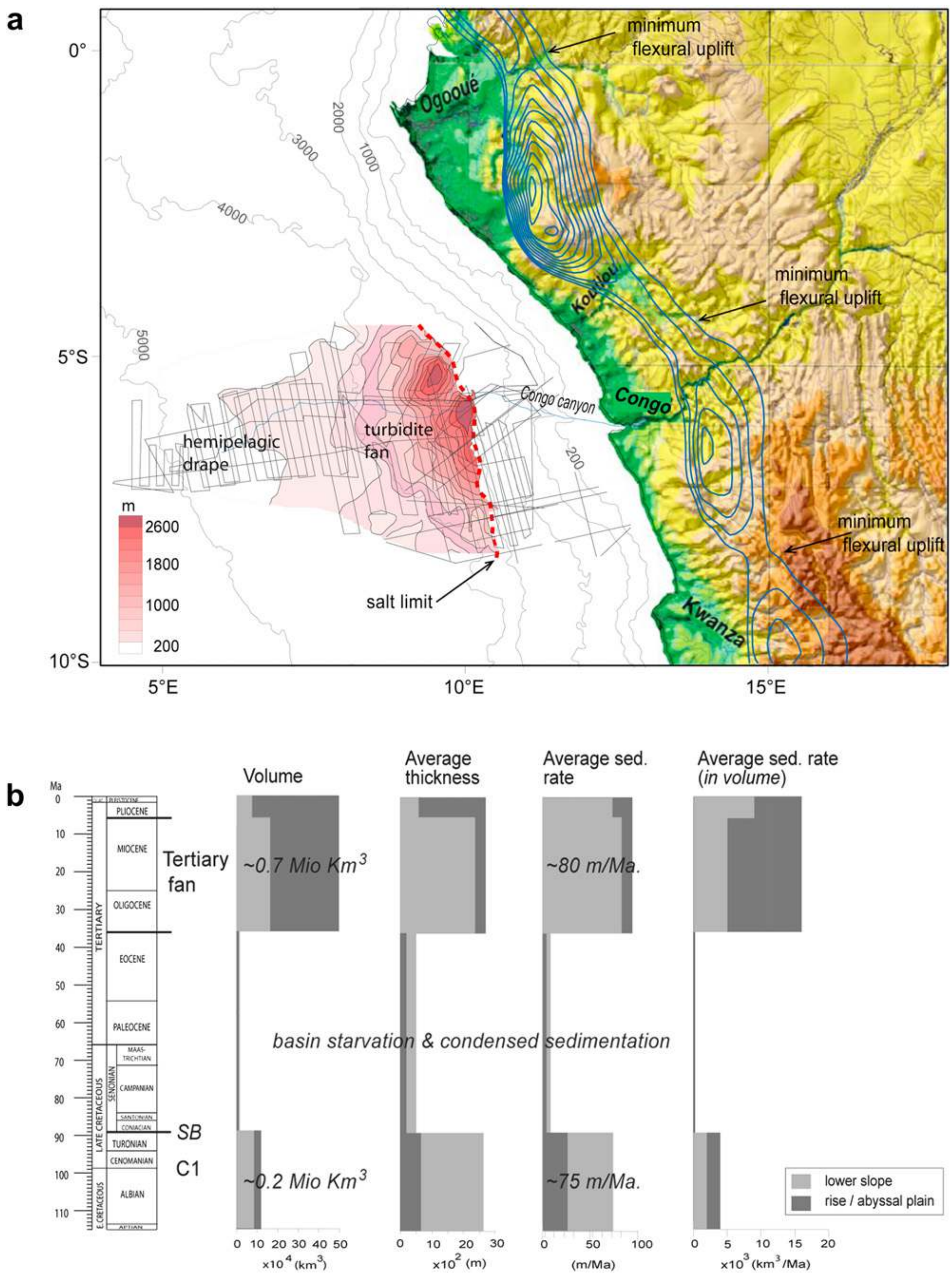

Fig. 7. a) Offshore: Isopach of C1 depicting a fan-shaped depocentre centred on the present-day Congo canyon – River outlet axis. Onshore: modelled peripheral flexural uplifts for a Te = 15 km from Fig. 6b (contouring every 10 m, first contour 20 m). b) Comparison between the compacted deposited volume and the average sedimentation rates of C1 and the Tertiary fan deposits on the lower lope and the rise/abyssal plain.

Additionally, the fact that the present-day Congo River cuts across one of the modelled lower flexural-uplift areas suggests the existence of an antecedent drainage (Fig. 7a). Evidences for this interpretation are found on the Congo River deep-incised gorge and the presence of several water falls along its course between Kinshasa and the sea (Goudie, 2005).

Although it is not possible to verify the exact palaeo-coastal drainage pattern during this time, and both the age and nature of the initial canyon incision are still unclear, our results strongly suggest that the Congo's outlet to the Atlantic has remained fairly stable since Late Cretaceous, and thus it probably sourced C1 deposits. Consequently, and contrary to previously proposed hypothesis, the Congo River was also an important sediment supplier to the Gulf of Guinea, among the Ogoué and Kwanza rivers, during Albian–Late Cretaceous. Therefore, the age of the Atlantic sedimentary system related to its exorheism is much older than previously proposed, e.g. Eocene (Emery et al., 1975; Uchupi, 1992), Oligocene (Reyre, 1984; Savoye et al., 2000), Upper Miocene (Uenzelmann-Neben, 1998), and Pleistocene (Giresse, 2005).

6.2. Implications for potential ultra-deep source rocks

The estimated age of C1 falls into one of the last-two major Cretaceous anoxic events registered off-shore west Africa: the early Turonian OAE2, which resulted in the deposition of organic carbon-rich (TOC up to 17% type I/II) upper-Cretaceous black shales (Wagner, 2002). Hence, we carried out the thermal modelling of the units deposited on the oceanic domain of the basin in order to

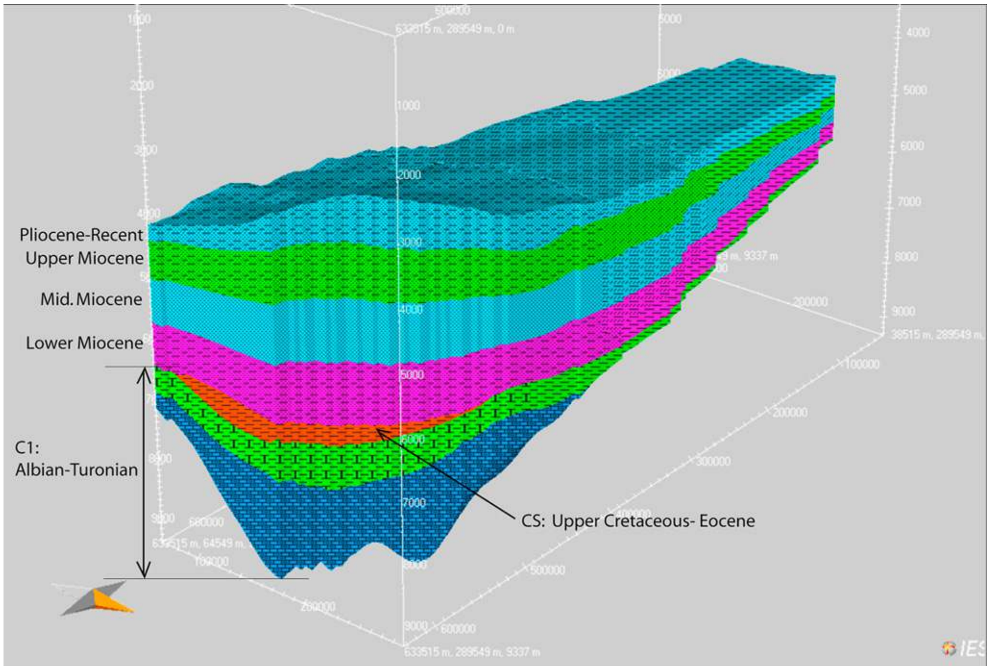

Fig. 8. Conceptual 3D geo-cube used for the thermal modelling of the sedimentary units deposited on the oceanic domain. The numerical mesh consists of 134 × 56 nodes with a grid spacing of 5 km.

evaluate the maturation history of a potential source rock within C1. We built a 3D numerical mesh consisting of 134 × 56 nodes, a grid spacing of 5 km, and 8 stratigraphic layers. Due to the absence of boreholes, the lithologies on the conceptual model are based on the extrapolation of the lateral age-equivalent facies. Thus, the facies fine-grained content increases basinward for each layer (Fig. 8). Material properties as porosity, permeability and thermal conductivity are assigned as lithology-dependent default values of the modelling software (Petromod™). C1 was modelled as being mainly composed of deep-water shaly carbonates containing a marine source rock with kinetic parameters of Type II(B) kerogen (Pepper and Corvi, 1995).

We tested three different palaeo-heat-flow scenarios based on the following models for a cooling oceanic lithosphere: (1) the plate model of Parsons and Sclater (1977) -PSM-, (2) a cooling half-spaced model -HS- with the same parameters of PSM, and (3) the GDH1 plate model of Stein and Stein (1992). The PSM and HS models predict a present-day heat flow of about 40 mW/m^2, whilst the GDH1 model predicts a much higher heat flow of 50 mW/m^2. Consequently, the results presented here are based on a heat-flow

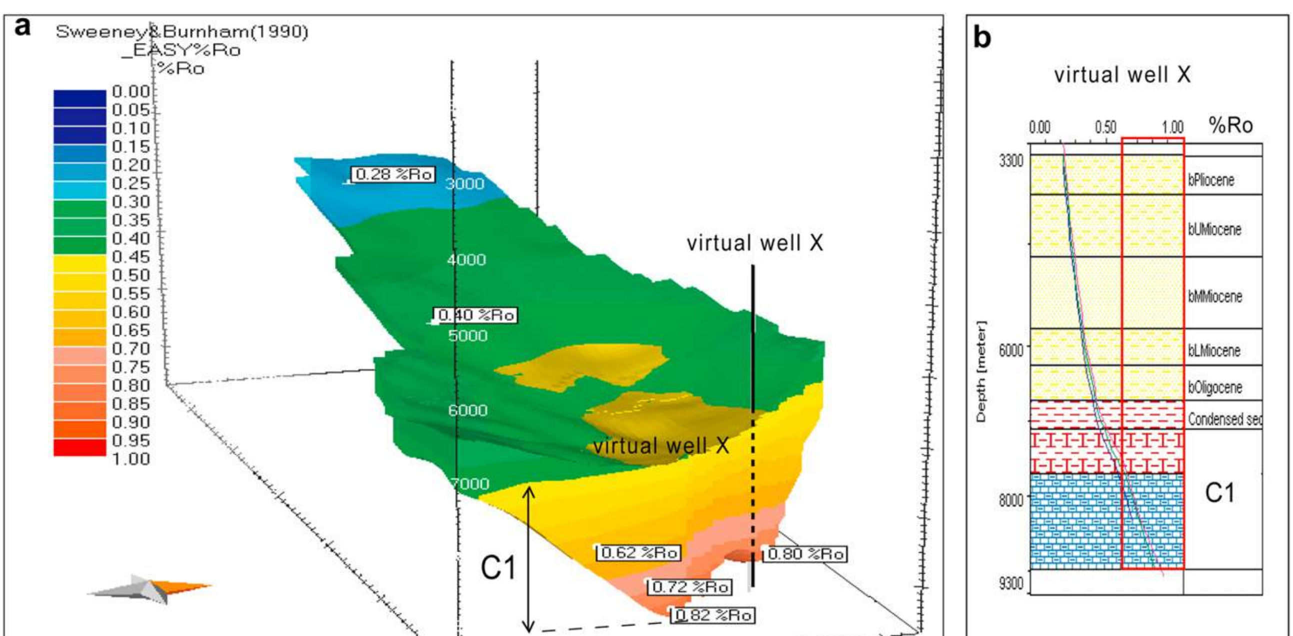

Fig. 9. a) Modelled 3D distribution of the present-day maturity of C1 expressed as vitrinite reflectance Ro (Sweeney and Burnham, 1990). The simulation was carried out using Petromod™ modelling software. b) Modelled Ro vertical distribution for a virtual well X suggesting that lower section of C1 is currently mature (Ro > 0.6%).

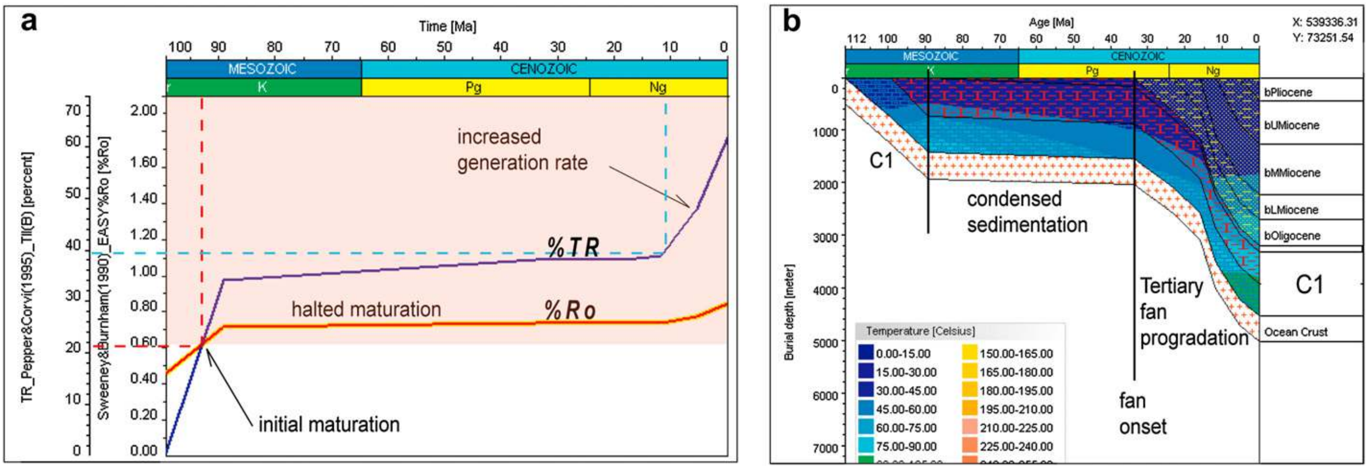

Fig. 10. a) Modelled evolution through time of the maturity Ro (Sweeney and Burnham, 1990) and the transformation ratio TR (Pepper and Corvi, 1995) within a cell of C1. b) Burial history and temperature evolution for virtual well X.

history derived from Parsons and Sclater's model as it best fits the particularly low present-day values of 42 ± 3 mW/m^2 (Lucazeau et al., 2004). The present-day sediment-water interface temperature is assumed to be about 5 °C at the base of the slope and the palaeo-water depth in this area is set to increase from about 500 m (Marton et al. 2000) to the present-day value of 3400 m (and much deeper basinwards).

The model predicts a continuous basinward decrease of the present-day maturity, expressed in terms of vitrinite reflectance (Ro), with maximum values located in the bottom part of C1 (Fig. 9a). Despite the low present-day heat-flow values, a virtual well "X" located near the base of the slope predicts that more than half of the deepest sections of C1 would have Ro values above 0.6% (Fig. 9b). This infers that the basal section of C1 is currently mature and, should it have source rock potential, it is likely to be generating hydrocarbons.

Comparison between the burial history of the virtual well "X" and the modelled maturity evolution for a cell within the bottom section of C1 indicates that the unit enters the oil window ($Ro > 0.6$) as early as by the end of its deposition during late Turonian (Fig. 10a). Since both burial and sedimentary thickness were not yet significant, the driving factor for this early maturation was probably the typically high heat flow of the then-young oceanic lithosphere. The following decreasing heat flow of the cooling oceanic lithosphere and the post-Turonian long period of condensed sedimentation, represented by unit CS, halted further maturation (Fig. 10b). Interesting is the fact that the sharp increase in sedimentation rates associated to the onset of the Tertiary submarine fan during early Oligocene does not seem to have enhanced the maturity trend as it would be expected. Nevertheless, a drastic increase in the hydrocarbon generation rate is predicted during the mid-Miocene, which may have been driven by the increase in sediment loading related to the basinward progradation of the fan into the abyssal plain. It is worth pointing out that these results represent the most favourable modelling scenario as they correspond to the bottom part of C1, which is the only section currently thermally mature.

7. Conclusions

This study clearly shows the existence of a large, and formerly unknown, Albian–Turonian unit underlying the Cenozoic Congo submarine fan that extends across the Continent-Ocean boundary on the Congo-Angola basin. The load of this unit containing a minimum of 0.2×10^6 km^3 sediments, in junction with its proximal age-equivalent deposits on the shelf and the Cretaceous depocenters of the Ogoué and Kwanza Rivers, may have caused an on-shore flexural-uplift stripe up to 100 m high, which probably influenced the location of the coastal palaeo-drainage. Moreover, our results suggest that the location of the Congo River's outlet has remained fairly stable since the Late Cretaceous and the basal unit was indeed sourced by a palaeo-Congo located nearby the present-day river. Additionally, thermal modelling suggests that the maturation history of the basal unit was initially mainly controlled by the high heat flow of the young Aptian oceanic crust, followed by the increase in sediment supply caused by the progradation of the Congo deep-sea fan during the Miocene. Hence, if there are organic carbon-rich intervals within the basal part of the distal upper-Cretaceous deposits, they are likely to be currently generating hydrocarbons.

In summary, the discovery of this significant depocentre has important implications for the continental palaeo-drainage of west Africa as it shows that, contrary to previous ideas, the Congo River has been a significant sediment supplier to the Atlantic since the Late Cretaceous. Furthermore, despite the typical present-day low heat-flow values of the oceanic lithospheres, the interplay between an initial high palaeo-heat flow and further significant sediment supply in areas of major river input, may favour the thermal maturation of potential ultra-deep source rocks on frontier exploration areas of mature passive margins.

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