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Geological constraints on the evolution of the Angolan margin based on reflection and refraction seismic data (ZaïAngo project)

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Abstract:

Deep penetration multichannel reflection and Ocean Bottom Seismometer wide-angle seismic data from the CongoAngola margin were collected in 2000 during the ZaïAngo cruise. These data help constrain the deep structure of the continental margin, the geometry of the pre-salt sediment layers and the geometry of the Aptian salt layer. Dating the deposition of the salt relative to the chronology of the margin formation is an issue of fundamental importance for reconstructing the evolution of the margin and for the understanding of the crustal thinning processes. The data show that the crust thins abruptly, from a 3040 km thickness to less than 10 km, over a lateral distance of less than 50 km. The transitional domain is a 180-km-wide basin. The pre-salt sediment layering within this basin is parallel to the base of the salt and hardly affected by tectonic deformation. In addition, the presence of a continuous salt cover, from the continental platform down to the presumed oceanic boundary, provides indications on the conditions of salt deposition that constrain the geometry of the margin at that time. These crucial observations imply shallow deposition environments during the rifting and suggest that vertical motions prevailedcompared to horizontal motionsduring the formation of the basin

Keywords: non-volcanic passive continental margin, crustal structure, transitional domain, sub-salt imaging, deep seismic reflection and refraction

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Summary
Deep penetration multi-channel reflection and OBS wide-angle seismic data from the Congo-Angola margin were collected in 2000 during the ZaiAngo cruise. These data help constrain the deep structure of the continental margin, the geometry of the pre-salt sediment layers and the geometry of the Aptian salt layer. Dating the deposition of the salt relative to the chronology of the margin formation is an issue of fundamental importance for reconstructing the evolution of the margin and for the understanding of the crustal thinning processes. The data show that the crust thins abruptly, from a 30 – 40km thickness to less than 10km, over a lateral distance of less than 50km. The transitional domain is a 180km wide basin. The pre-salt sediment layering within this basin is parallel to the base of the salt and hardly affected by tectonic deformation. In addition, the presence of a continuous salt cover, from the continental platform down to the presumed oceanic boundary, provides indications on the conditions of salt deposition that constrain the geometry of the margin at that time. These crucial observations imply shallow deposition environments during the rifting and suggest that vertical motions prevailed - compared to horizontal motions – during the formation of the basin.

Key words: non-volcanic passive continental margin, crustal structure, transitional domain, sub-salt imaging, deep seismic reflection and refraction

Introduction

Due to its economic potential, the continental margin offshore Gabon, Congo, Zaire and Angola - from the shoreline to the presumed ocean boundary - has been the subject of intensive seismic surveys, conducted during the last few years by oil companies, using standard, industrial MultiChannel Seismic (MCS) techniques. While these studies provide an advanced knowledge of the post-salt sedimentary cover, the pre-salt sedimentary layers and crustal structure remain nevertheless largely unknown due to the presence of a massive Aptian Salt sequence (middle to upper Aptian: 117 to 112.2 Ma, according to the time table of Gradstein *et al.,* 1994) which perturbs the seismic propagation when using a conventional seismic acquisition system. Though, most widely used models invoke, for instance, pure stretching and/or simple shear to explain the thinning of the continental crust. These models imply large horizontal motions, which should perturb the syn-rift sedimentary layers above the basement. The study of the salt and pre-salt sedimentary sequences, together with the crustal geometry, is therefore essential to understand the process of margin formation, as any kind of crustal motion should be imprinted in these layers.

In this paper, we present new MCS seismic data that were acquired during the ZaïAngo cruise (April 2000), a joint project between Ifremer, the french oceanographic institution, and the oil company Total. These data were collected simultaneously with wide-angle seismic (Ocean Bottom Seismometer) data that are presented in a companion paper (Contrucci *et al*, 2004). The geometry of the salt and pre-salt layers is discussed here. The results will allow us to present a pre-breakup tectonic evolution that will constrain future models of margin genesis for the Angolan margin.

Geological setting

The South Atlantic Ocean, between Africa and South America, is divided into 4 segments (**Figure 1**): i) the equatorial segment, between about 10°N and the Equatorial Fracture Zones system (Saint-Paul, Vema and Romanche FZ); ii) the central segment, between the Romanche FZ and the Walvis/Rio Grande Ridges; iii) the southern segment, between the Walvis/Rio Grande Ridges and the Falkland-Agulhas FZ; and iv) the Falkland Segment, south of the Falkland-Agulhas FZ.

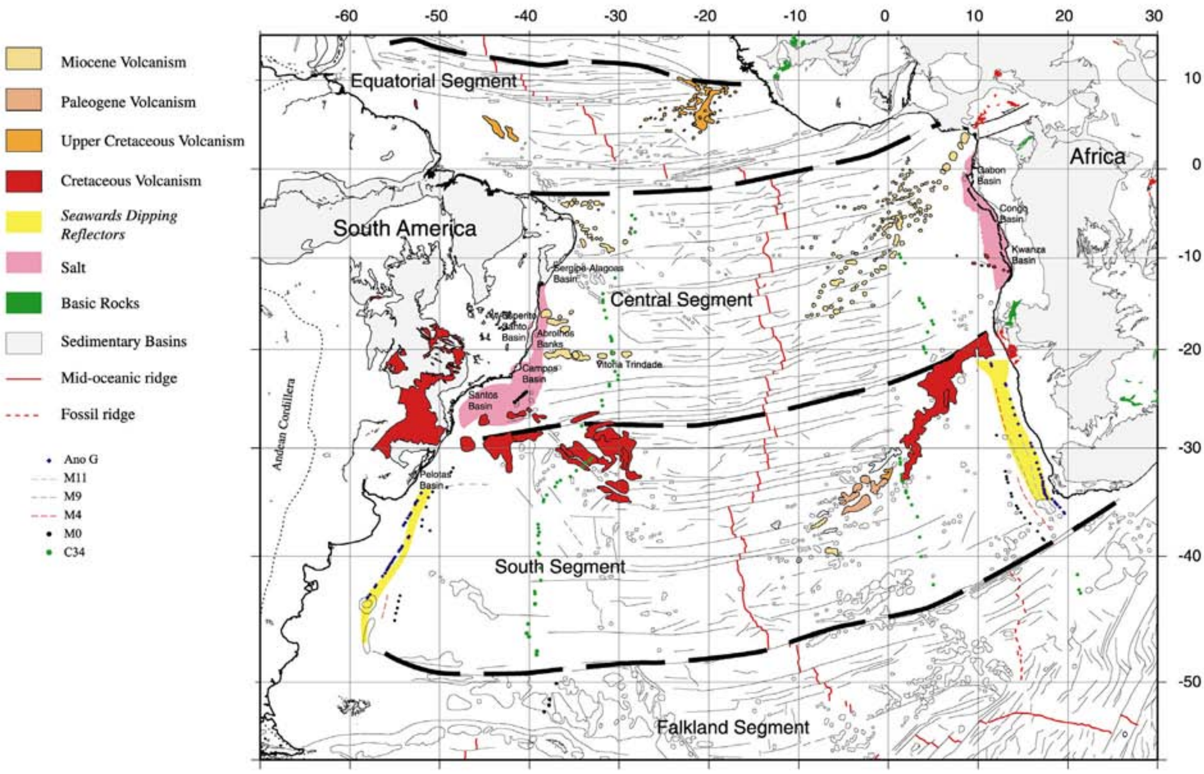

Figure 1: General structural map of the South Atlantic Ocean. Boundaries between the 4 segments are in broken black lines. Fracture zones and seamounts are based on interpretation of the gravity map (Sandwell and Smith satellite derived gravity data, grid 1 x 1 minute, pers. comm.). The salt boundary is in pink (after Pautot *et al.*, 1973, Renard & Mascle, 1974, Emery *et al.*, 1975, Leyden, 1976, Mascle & Renard, 1976 and Lehner & De Ruiter, 1977), SDR boundaries (yellow areas) are indicated after Hinz *et al.*, 1999 (South America) and Bauer *et al.*, 2000 (Africa). The M-sequence magnetic anomalies (symbols or thin color dotted line) is taken from the interpretation of Rabinowitz & LaBrecque (1979) in South Africa, from Cande & Rabinowitz (1977) in South America, whereas the C34 anomaly is based on the interpretation of Klitgord & Schouten (1986).

The South Atlantic Ocean started opening 140 Ma ago (Lower Cretaceous), during the western Gondwana break-up. In the initial reconstructions that have been proposed, it is impossible to close the southern segment (between Walvis and Falklands) together with Equatorial and Central segments, without inferring intraplate deformation in the African Plate (Burke & Dewey, 1974; Pindell & Dewey, 1982; Fairhead, 1988; Guiraud & Maurin, 1992), in the South American Plate (Curie, 1984) or in both plates (Unternehr *et al.,* 1988; Nürnberg & Müller, 1991; Moulin, 2003). Moreover, M-sequence magnetic anomalies are only observed in the southern segment (M0 to M11, Rabinowitz & Labreque, 1979). On the other hand, the central segment is known to be characterized by the presence of an Aptian salt cover (absent south of the Walvis-Rio Grande Ridges), while seaward dipping reflectors (SDRs) are well documented in the southern segment, reflecting a distinct evolution. It is difficult to date the early stages of seafloor spreading in the central segment due to the absence of well-identified magnetic anomalies.

Pre-salt sediments are only known on the continental shelf by industrial wells: i) Lower Carboniferous to Trias–Jurassic times are characterized by fluvio-lacustrine sediments; ii) The Neocomian to Mid-Barremian (144,2 to 124 Ma, according to Gradstein *et al*., 1994) episode is characterized by deposits of conglomerates, clastics and clay, and by a high tectonic activity. This episode is sealed by the Pointe Noire unconformity (Tessereinc & Villemin, 1990; Vernet *et al*., 1996); iii) a later episode, characterized by a lacustrine sedimentation deposited during Barremian to Middle Aptian times (127 to 117 Ma), followed by the deposition of a thin layer of marine sediments known as the Chela layer. This latter episode is characterized by a low tectonic activity and related to the formation of offshore basins such, as for instance, the Dentale basin, off Gabon (Tessereinc & Villemin, 1990; Vernet *et al.,* 1996). As far as the tectonic significance is concerned, the authors agree with the following: i) the rifting starts at the beginning of the Neocomian times (144,2 Ma); ii) the tectonic activity ceases on the platform at the Intra-Barremian times, whereas it continues in the basin. This last statement leads some authors (Karner *et al*., 1997) to propose a rift propagation along and across the region as a function of space and time. However, even if the tectonic activity on the platform and in the basin stopped at different times, there is no evidence, from the data available in the basin, that they could not have both started during the same period (as early as the base of the Neocomian time). This point will be discussed in the following.

The post-salt history (Séranne *et al*., 1992) shows a change in the nature of sedimentation, from carbonate deposition to silico-clastic progradation, which supposedly occured at the base of the Oligocene times (33.7 Ma). This change in sedimentation could be related to an uplift of the Southern Africa Platform, which resulted in an important erosion and an increase of the sedimentary loading (Bond, 1978; Burke, 1996; Lunde *et al*., 1992; Walgenwitz *et al*., 1990; Walgenwitz *et al*., 1992 in Anka & Séranne, 2004).

To date the deposition of the salt relative to the chronology of the margin formation is an issue of fundamental importance, for the reconstruction of the evolution of the margin and the understanding of the crustal thinning processes. The salt layer - less than 1km thick - was formed during Aptian times. There is a general agreement on the duration of the salt deposition, of about 5 Ma (e.g. Doyle *et al.,* 1977; Doyle *et al.* 1982; Teisserenc & Villemin, 1990; Mussard, 1996).

If the salt deposition is pre-breakup (i.e. deposited before the oceanic seafloor spreading occurs) as proposed by various authors (Evans, 1978; Brice *et al*., 1982; Ojeda, 1982; Guardado, Gambo & Lucchesi, 1989; Duval, Cramez & Fonck, 1992; Davison, 1999), then the pre-salt sediment infill is also pre-breakup and the substratum is continental or sub-continental (for instance, thinned continental crust intruded by mantle material immediately prior to sea-floor spreading, as proposed, for instance, by Whitmarsh & Miles (1995) for the Iberia margin). If the salt is post-breakup, as proposed by others (Nürnberg & Müller, 1991; Guiraud & Maurin, 1992; Karner *et al.,* 1997; Abreu, 1998; Fonck, Cramez & Jackson, 1998; Marton *et al*., 2000), then it is possible that the salt was partly deposited on a non-continental substratum (as suggested by Jackson, Cramez & Fonck, 2000).

Karner *et al.* (1997) suggest, on the basis of subsidence modeling, that the shelf evaporites (named “Loeme formation” on the Congo and Cabinda margins) and the outer-basin diapiric structures are not the same salt formation. Taking into account the post-evaporite sediment thickness observed across the Congo margin and the prevailing shallow water conditions on the platform (imposed by the evaporites of the Loeme formation), these authors cannot model correctly the subsidence of the margin. Therefore, they argue that the outer basin formed in deep water condition (2000m) and that Loeme equivalent evaporites cannot exist in the outer basin. The observed outer diapiric structures could be 1) Pre-Loeme syn-rift evaporites (5 to 10 Ma older), 2) deep-water equivalent salty shales of the Loeme formation. They argue that this interpretation could explain the different geochemical composition between the salt formation: for these authors, "the Loeme evaporites do not represent a continuous salt blanket draping the margin but rather a sequence of spatially and geochemically distinct salt pockets along the margin".

However, the interpretation of the seismic profiles, for example, the interpretation of Marton *et al.* (2000), based on industrial seismic profiles, show a continuous salt blanket on the Lower Congo and Kwanza basins. They infer that this salt was deposited in a post rift sag basin.

2 Study area and data

The study area is located in the central segment, off the West African margin, between Congo, Zaire and Angola **(Figure 2)**. The sedimentary basins investigated during the ZaïAngo project are the Lower Congo basin and the northern part of the Kwanza basin, between 5°S and 8.5°S, which belong to a series of Mesozoic basins, that developed during the Late Jurassic and Neocomian times on the conjugated margins of Africa and Brazil. The Kwanza basin, limited at the east by the 200m water depth contour line and at the west by the presumed oceanic crust boundary, is about 320km wide, covering an area of 22000km^2. The main target, the Lower Congo basin, is about 250km wide and located between Gabon and Angola, between the Mayumba apron and the Ambrizete Arch.

3 Previous data:

Due to their economic importance, the Mesozoic basins of the South Atlantic conjugated margins were intensively explored by the oil industry. Numerous seismic grids (5km x 5km) exist for the conjugated continental platforms, but these data, like the 3D seismic block data, are proprietary and not accessible to academic research. In addition, data from academic institutions can be in some cases difficult to obtain, due to exclusivity related problems in exploration permits areas. The available, non-proprietary, seismic data that existed previously to the *ZaïAngo project* between the Equatorial Atlantic Fracture Zones and the Walvis/Rio Grande Ridges consist of (**Figures 1 & 2**):

- single channel seismic lines, collected by academic institutions (Ifremer, 1971; Lamont-Doherty, 1966-1979; Univ. of Texas, 1979; Woods Hole, 1972) in the late 60's and early 70's for regional reconnaissance. On the African margin, profiles are generally perpendicular to the margin, spaced every 100 to 200km. On the Brazilian margin, most profiles are located in the Campos and Santos basins (relatively few profiles exist north of Campos). Numerous single channel seismic lines shot on the continental platform for the oil industry are also available. In the oceanic domain of both margins, these data provide information about the top of the crustal basement, and, in some places, from the base of the Aptian salt, they do not provide any information related to the syn-rift series.

- 2D multichannel seismic (MCS) lines. On the African margin, long, regional MCS lines were collected off Gabon in 1989 during the P. R. O. B. E. (Proto Rift Ocean Basin Evolution) Programme; pre-salt, intra-crustal and Moho reflections are clearly visible at depths of 10 s (two way travel time: twt) in the seismic sections, which provide informations on the deep structure of the margin and on the ocean-continent transition off Gabon (Rosendahl *et al.*, 1991); a few other published seismic sections (released by the oil industry) offer additional informations on the sub-salt layers, but only on the continental platform (Marton *et al.,* 2000). On the Brazilian margin, only two regional sections have yet been released by the oil industry: Mohriak *et al.* (1998) published one line (239-RL-242) shot across the Sergipe Alagoas basin, that offers an image of the sedimentary series, but no clear image of the deep structures, although coherent signal is visible down to 9-10 s (twt); Abreu (1998) published line drawings sampling the deep margin structure across the Pelotas basin.

refraction surveys. The refraction experiments that were conducted in the early 70's do not actually provide fully reliable information on the deep structure of the conjugated margins.

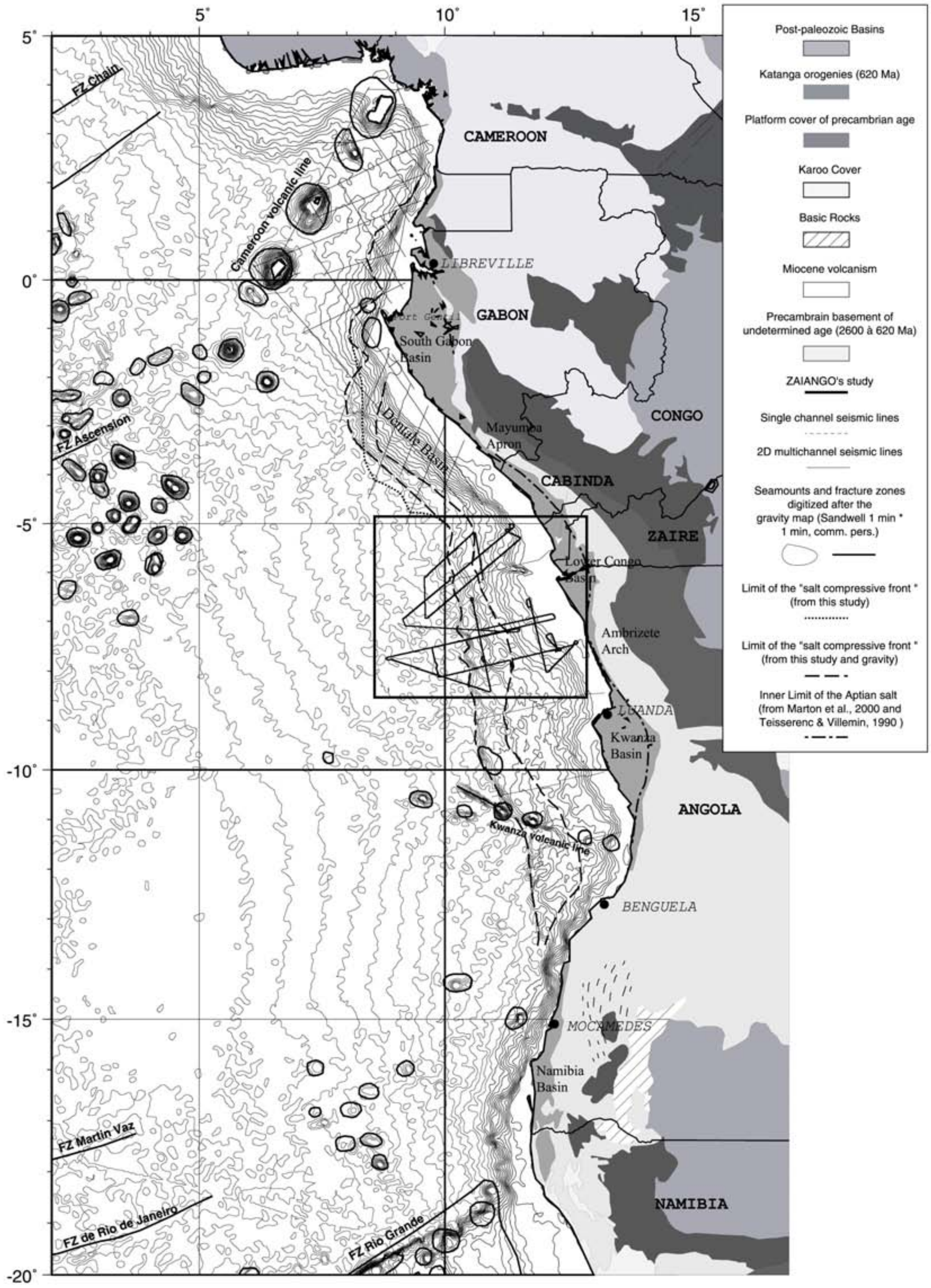

Figure 2: General predicted bathymetry map (after Smith & Sandwell (1997)) of the West African margin between the equatorial fracture zones (to the North) and the Walvis Ridge (to the South). Fracture zones and seamounts are based on interpretation of the gravity map (Sandwell and Smith satellite derived gravity data, grid 1 x 1 minute). Onshore geologic structures are based on the digitisation of the international tectonic map of Africa (Choubert *et al*., 1968). The location of the ZaïAngo study area is reported in red and the located plan by a black line. The black dotted lines correspond to the limit of the salt compressive front. These limits are based on the interpretation of Moulin (2003) from the data of Ifremer (Walda, Zaiango), Woods Hole, the University of Miami (P.R.O.B.E.) and the oil industry (Marton *et al*., 2000 (BP), Vernet *et al*., 1996 (Elf), Teisserenc & Villemin (1990) (Elf) and Reyre (1984) (Elf). The inner limit of the salt is based on Marton *et al*., 2000.

On the African margin, ESPs (**E**x<u>p</u>anded **S**pread **P**rofiles) were shot in the mid-80's to sample the deep structure of the South Gabon basin (Wanesson *et al.,* 1991); OBS (**O**cean **B**ottom **S**eismometer) data were also collected in the late 90s, to study the structure of the Namibia margin (Bauer *et al.,* 2000), south of Walvis Ridge.
On the Brazilian margin, three experiments were conducted with sonobuoys (Ewing *et al.,* 1969; Leyden *et al*., 1971; Kowsmann *et al*., 1977), but no refraction experiment involving ESPs or OBSs is, to date, reported. Unfortunately, there are no seismic data from the deep structure of the Brazilian homologs of the Lower Congo and Kwanza basins (e.g. the Espirito Santo basin); the presence of volcanism, Eocene (Abrolhos Bank) to present-day (Vitoria Trinidade volcanic ridge) together with the salt layer represent a strong seismic screen that make seismic investigations difficult.
- gravimetric surveys. On the African margin, gravimetric models were proposed for the South Gabon and Lower Congo basins (Karner *et al.*, 1997; Watts & Stewart, 1998; Pawlowski, 1999; Wilson *et al*., 2003; Dupré 2003; Dupré *et al.*, 2003; Lucazeau *et al.*, 2003). On the Brazilian margin, due to the absence of *ad hoc* (wide angle) seismic data, information on the deep structure of the margin mainly comes from gravimetric models: by Gomes *et al.* (2000) for the Nordeste margin; by Ussami *et al.* (1986), Castro (1987), Mohriak *et al.* (1998), Karner & Driscoll (1999), Mohriak *et al.* (2000) for the Sergipe and the Tucano (onshore) basins; by Mohriak & Dewey (1987) and Mohriak *et al.* (1990) for the Campos basin.
The results presented here are based on all those data and on unpublished data from the oil industry (Total) and from the ZaïAngo programme. The interpretation of the industrial MCS lines, verified by Total with all available drillholes, provide valuable informations on the post-salt sediment series, while the ZaïAngo data (MCS and the combination of MCS and OBS refraction data, after Contrucci *et al* (2004)) provide information on the pre-salt structures that were left unrevealed so far using conventional techniques.

4 New data used in the present study
These data consist of (**Figure 3**):

• A set of 6 proprietary, regional, MCS lines (A84-102, GW A88-1079GF, A84-74, GW A88-1075, 97 MPS-201 and 92HM-76) that were acquired and interpreted by the oil company *Elf* (before the merge with Total) using all available information (seismic grids and drillings) from the continental platform. Without drillhole control in the deep offshore domain, the drillhole data from the continental platform were extrapolated to the slope foot and even further, down to the presumed ocean crust.
• MCS reflection data and OBS refraction data collected in March 2000 during the ZaïAngo programme (Savoye*, pers. comm.,* 1999), a joint project conducted in the years 1998-2001 by Ifremer and Elf. 17 profiles were shot during the ZaïAngo cruise, for a total of 3180km of seismic lines. Eight regional lines were simultaneously recorded on the multichannel streamer towed behind R/V Nadir and on OBSs deployed on the seafloor. Five profiles (3, 7, 11, 12, 14) were shot across and three (1, 9, 17) along the strike of the margin:
  • Profile 3 is 320km long (with 9 OBSs, evenly distributed every 25km over a 200km long section) and partly implemented along industrial lines A84-74 and GWA88-1075.
  • Profiles 7 and 11 were merged into one single line, named « 7+11 » hereafter. This line is 400km long (with 26 OBSs, unevenly distributed every 7.5 or 15km approximately over a 320km long section) and partly implemented along line A84-74.
  • Profile 12 is 210km long; with 5 OBSs, evenly distributed every 20km over a 80km long section.
  • Profile 14 is 270km long (with 14 OBSs, evenly distributed every 20km; oriented NE-SW; crossing the Zaire canyon) and partly implemented along lines 97MPS-201 and 92HM-76.
  • Profile 1 is perpendicular to lines 3 and « 7+11 »; 180km long, with 5 OBSs evenly distributed every 25km in its central part.
  • Profile 9 is perpendicular to lines 3, « 7+11 » and 12; 180km long, with 6 OBSs evenly distributed every 25km in its central part.

- Profile 17 is perpendicular to line 14; 100km long; with 4 OBSs spaced about every 20km.

In addition: i) one 100km long line (profile 2), implemented 35km to the south of line GWA88-1079GF, was recorded on 3 landstations; and ii) a number of lines (4, 5, 6, 8, 10, 13, 15 and 16) were shot without OBS, and recorded on the MCS streamer only. The analysis presented hereafter is based on the whole dataset collected during the ZaïAngo programme. For sake of brievity, in this paper we only present the seismic sections of profiles 3, “7+11” and 14, which are calibrated in the post-rift sequence by industrial seismic lines of Total.

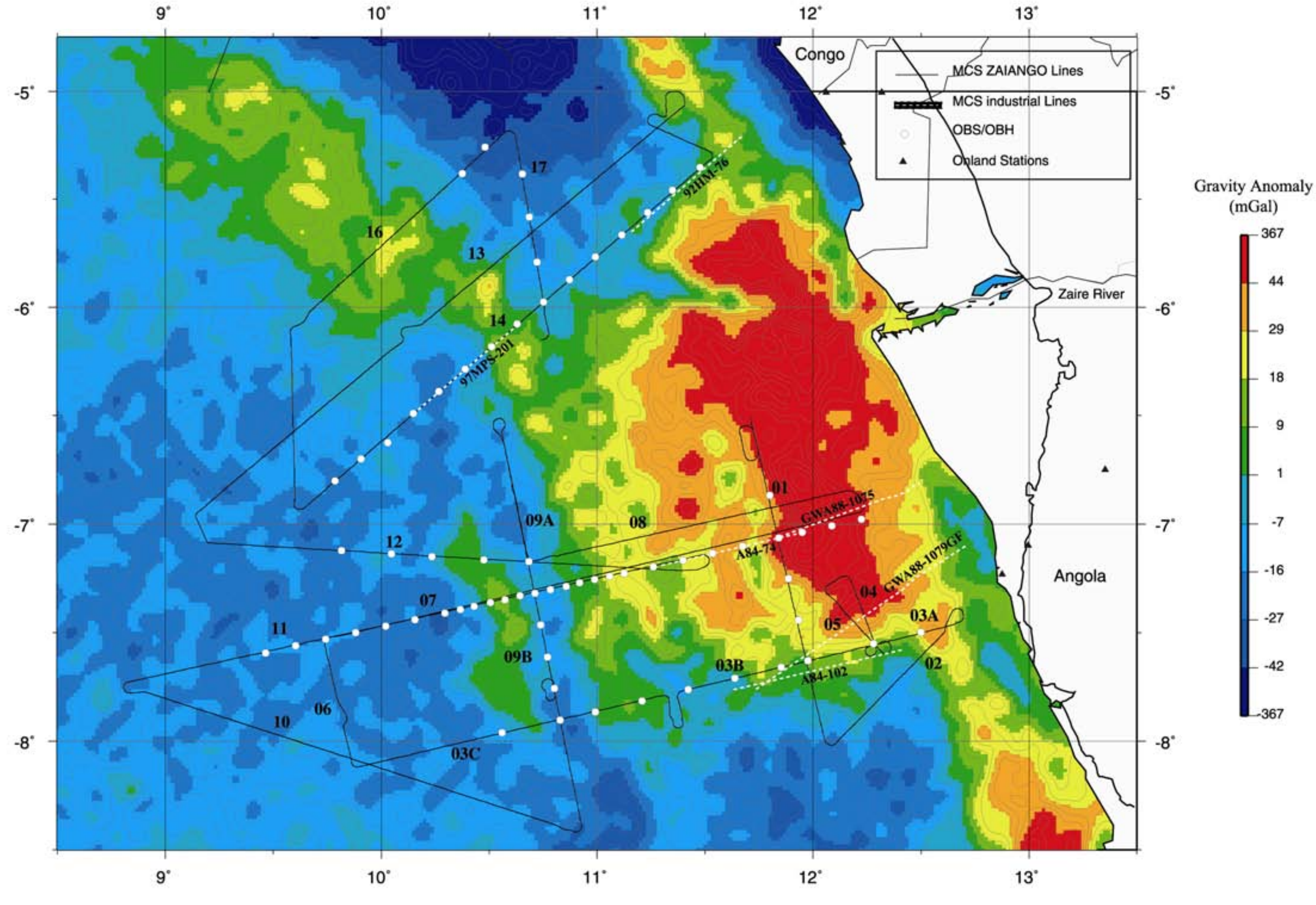

Figure 3

Figure 3: Gravimetric map (Sandwell and Smith satellite derived gravity data, grid 1 x 1 minute) of the survey area and location of the seismic profiles, including the ZaïAngo lines (black lines, numbered from 1 to 17) and the industrial lines from *Total* used in the present study (in white tick: A84-102, GWA88-1079 GF, A84-74, GWA 88 -1075, 97MPS-201, 92HM-76). OBS locations (white dots) and land stations (black triangles) are indicated. The boundary between the Cretaceous and the Pan-African domains is indicated onshore.

5 Seismic source and data processing

The objective of the ZaïAngo cruise was to obtain seismic information on the deep structures located beneath the salt layer, at a depth of about 8 to 12 s (twt) below sea-level - 15 to 35km in depth -, by simultaneously recording MCS reflection data on a 4.5km long digital streamer, and refraction data on OBSs. The shooting vessel, R/V Nadir, had a maximum towing capacity of 12 guns, and a maximum air capacity of 1360 m3/h compressed at 140 bars. Due to these practical constraints, a compromise was found, in order to produce as much energy as possible for refraction seismic and MCS reflection profiling. For simultaneous refraction and MCS data recording, the seismic source consisted of a 4805 cu-inch array of 12 airguns (8 x 550 cu-inch, 2 x 75 cu-inch and 2 x 150 cu-inch), towed 24 to 27 m below the sea surface and fired every 100 m (about 40 s shot interval). For reflection profiling only (on the lines with no OBSs), the source consisted of a 3155 cu-inch array of 9 airguns (three, 550 cu-inch, airguns were turned off), fired every 75 m (about 30 s shot interval). The source arrays were used in a way derived from the « single bubble » mode (Avedik *et al.,* 1993), which is based on synchronizing the signature of the airguns on the first bubble oscillation, instead of on the first signal peak. This procedure maximises energy in the lows frequencies. However, because we had to use a limited number of large airguns, mainly of identical volume (8 Bolt guns of 550 cu-inch each), the arrays were not tuned exactly as described by Avedik *et al.* (1993) who used smaller Sodera « Generator – Injector » airguns and could play on many parameters to refine the tuning, such as the air gun volume.

Data processing was performed at the Marine Geosciences Department of Ifremer. Different processing parameters and software packages were tested, depending on the different geological environments (shelf, slope, oceanic domain, salt diapir area, etc). A standard processing sequence was then applied to the MCS data, with adapted parameters and using the Geovecteur software. This sequence mainly includes: band-pass filtering; CDP collection; spherical divergence correction; anti-multiple; depth dependent dynamic equalization; external mute; dynamic corrections; velocity analysis every 200 CDP; stack; time dependent filtering (0 – 5000 ms: 3 - 5 – 40 – 50 Hz; 5000 – 7000 ms: 3 – 5 – 25 – 35 Hz; 7000 – 15000 ms: 3 – 5 – 15 – 20 Hz); dynamic equalisation; Kirchoff migration using a constant velocity of 1500 m/s; F-K filtering (see Contrucci *et al.,* 2004, for detailed explanations). An advanced processing sequence was tested on Profile 3ab at the *Total* Processing Centre in Pau but these tests did not improve the seismic image significantly, and finally, the standard profiles were used in our analysis.

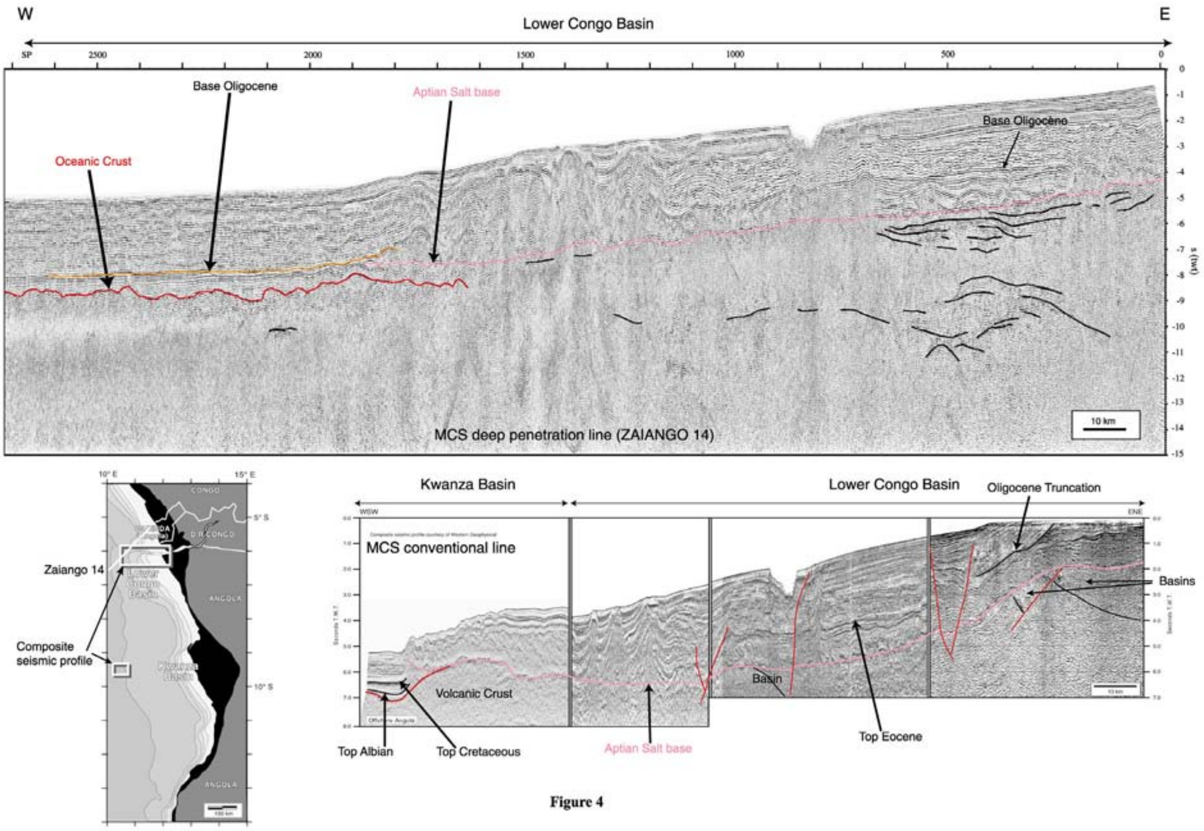

Figure 4: Comparison between ZaïAngo line 14 and one composite profile based on conventional seismic data acquired by Western Geophysical near the study area, across the Zaire Canyon (after Cramez & Jackson, 2000). The ZaïAngo profile is migrated using a constant velocity of 1500 m/s. Note the difference in resolution for the post-salt series and the information provided by the ZaïAngo data beneath the salt screen.

The seismic data generated by the non-conventional "single bubble" air gun array (Avedik *et al.,* 1993) provide an image of deep structures located below the Aptian Salt layer that were left unrevealed so far using conventional MCS techniques (**Figure 4**). However, the resolution in the post-salt sediment series obtained with the ZaïAngo source is relatively poor compared to conventional, industrial seismic sources. Post-salt seismic units are decipherable in the ZaïAngo data, but the shape of the diapirs – as well as the base of the salt layer in the diapirs area – is hardly resolvable.

Therefore, in the post-salt sediment series, we have systematically worked with the available industrial seismic lines and with the control provided by the numerous drill holes located on the shelf and on the upper part of the continental slope. By using the *Charisma* software, eight reference seismic horizons defined on the industrial lines, from the base of the Pliocene to the base of the Aptian salt layer, were reported on the ZaïAngo sections.

6 MCS data analysis

Based on the available industrial seismic lines (courtesy of Total), and MCS reflection data (together with OBS refraction data) from *ZaïAngo*, the study area is divided in 4 zones, as shown in **Figure 5** (seismic sections) and in **Figure 6** (structural map). Zone I corresponds to the continental platform domain. Zone II is the continental slope domain. Zone III is a transitional domain, between the foot of the continental slope and what can be unequivocally defined as the oceanic crust. Zone IV is the ocean crust domain.

Zone I (the continental platform domain) was hardly covered during the ZaïAngo cruise, because of logistical and safety reasons, except with some small parts of profiles 2 and 3. Based on gravity data (Watts & Stewart, 1998; Contrucci*., pers. comm.,* 1999), Zone I consists of unthinned, 30 to 40km-thick continental crust.

Zone II (the continental slope domain), is about 50km wide (**Figure 6**). It is mainly covered by industrial seismic lines and by ZaïAngo lines 2 and 3. It can be sub-divided into three sub-zones (IIa, IIb and IIc), characterized by different basement slope dip angles: 11°, 22° and 11°, respectively (**Figures 5 and 7**). Seismic lines from the oil industry (GWA88-1079GF, GWA88-1075 and 92HM-76) and ZaïAngo seismic profiles 2 and 3 provide valuable information on the deep structure of this region (**Figure 7**):

• Top of the basement deepening mainly occurs in Zone II, over a distance of less than 50km, from about 1s (twt) to about 5 s (twt) (or from about 3km to 10km in depth).

• Only one or two tilted blocks are visible.

- Where present, tilted blocks are observed only on the upper part of the slope, in Zone IIa. Outside Zone IIa, there is no seismic evidence for any significant deformation of the syn-rift sediment infill. The few observed tilted blocks have a lateral dimension of about 10km, and a maximum offset ranging between 2 and 4km, assuming sediment seismic velocities of 5.5 km/s. The average dip angle of the faults limiting the tilted blocks ranges between 50° and 70°. The sediments layering is fan shaped and sealed by a discordance, which is assumed to be intra-barremian in time [Reyre; 1984; Teisserenc & Villemin, 1990; Vernet *et al.,* 1996]. Depending on the stratigraphic scale, the age of this discordance ranges between 115 Ma [Haq *et al.,* 1987; Odin & Odin, 1990] and 128 Ma [Harland *et al.,* 1990].

• The pre-salt sediment layers are parallel to the salt layer, onlapping the continental basement. Near the tilted blocks, the pre-salt basin forms a wedge shape; its thickness decreases, from 2 s (twt) - 5km - at the slope foot, to 0.1 s (twt) - about 500m - on the upper part of the slope. This is clearly visible on the industrial seismic lines GWA88-1979 GF, GWA88-1075, 92HM-76, which are aligned with ZaïAngo lines 3, 7-11 and 14, respectively (See for instance Line GWA88-1979GF on **Figure 7**). The absence of apparent deformation affecting the pre-salt sedimentary cover suggests that the tectonic motions that may have occurred between the Neocomian and the Upper Aptian (144,2 to 112.2 Ma) times, were, if any, relatively limited.

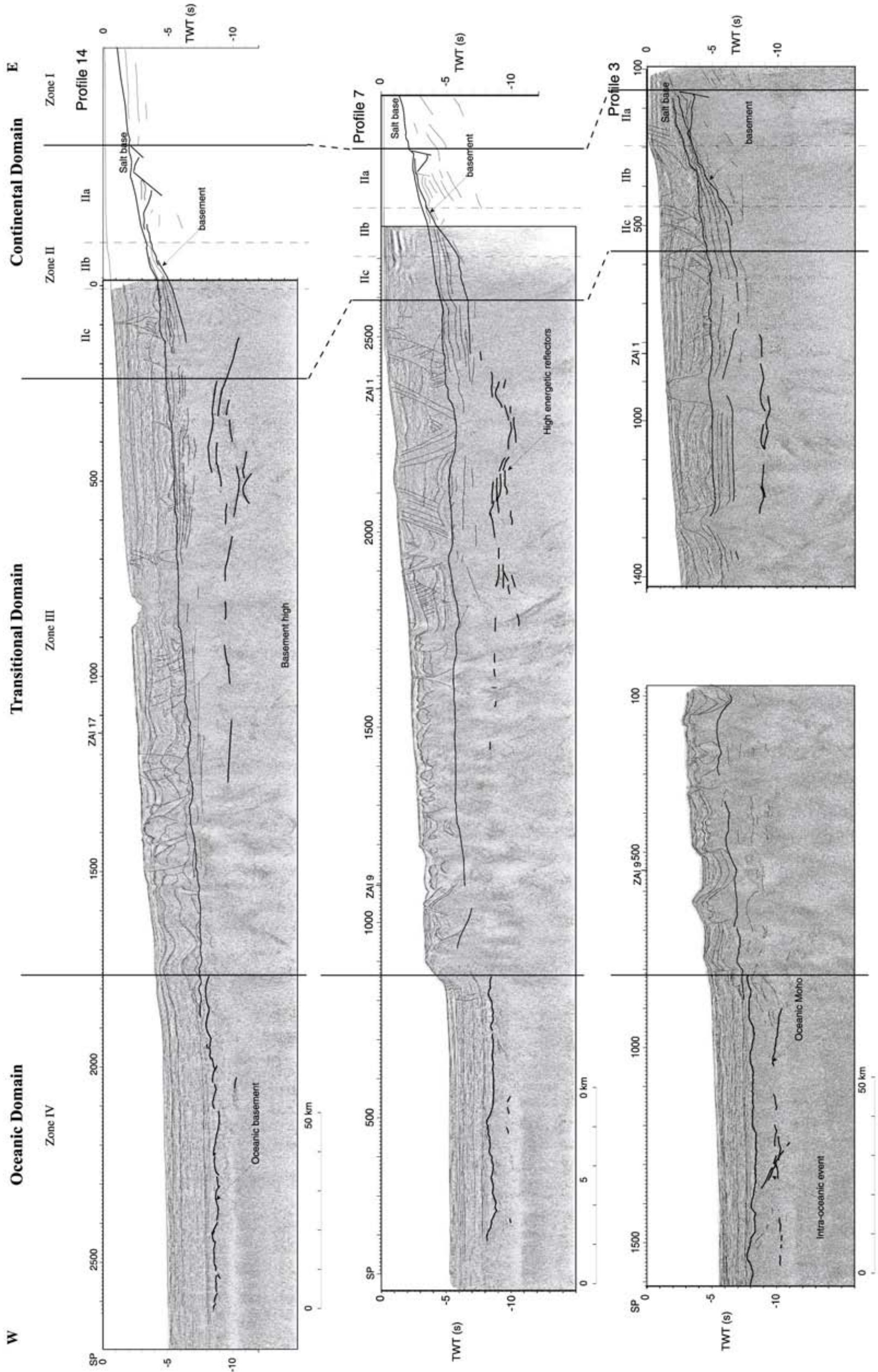

Figure 5: The three major seismic ZaïAngo transects (14, "7+11" and 3, respectively) shot across the margin. Line drawings in the post-salt sediment layers and near the coast are based on the interpretation of the industrial lines (courtesy of *Total*). The salt base and the basement are underlined by bold line drawings. Black, vertical lines delineate the boundaries between the different structural domains and zones I to IV. Vertical, ticked lines indicate the boundaries between the different secondary zones

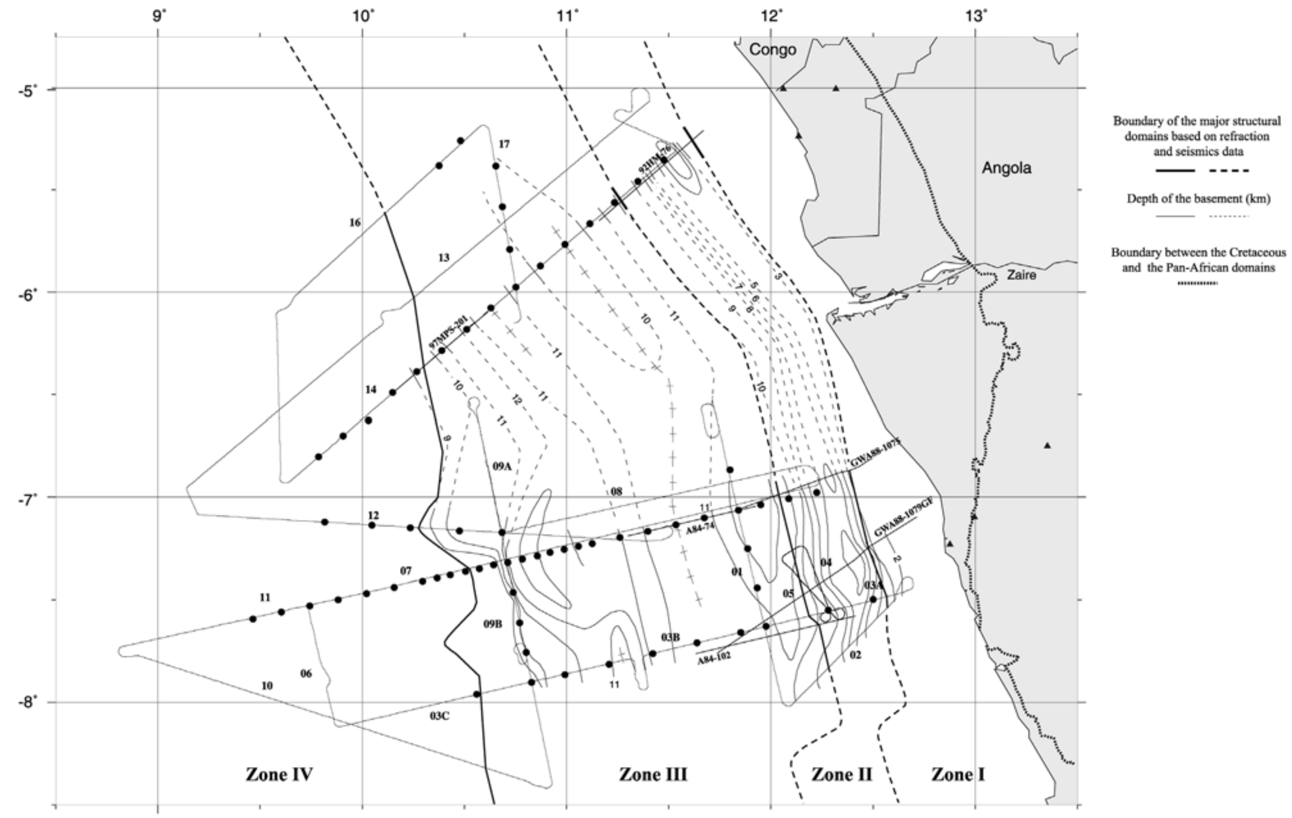

Figure 6: Structure contours on basement in the Lower Congo Basin, based on the OBS data of the Zaiango profiles (Contrucci *et al*., 2004). Contours are at 1km intervals (sea-level datum). Black thick lines delineate the major structural domains based on seismic and gravity data: zone I is the unthinned continental domain; zone II is the area where crustal thinning mostly occurs; zone III is the transitional domain; and zone IV is oceanic. The location of the Zaiango and industrial profiles are indicated in black line, the OBS in black circles, the landstations in black triangle and the Cretaceous/Panafrican boundary is a black thick dotted line.

Zone III is sampled by most ZaïAngo seismic lines (**Figures 5 & 8**). Its length, between the foot of the continental slope to the presumed oceanic crust boundary, is between about 160km (on ZaïAngo profile 14) and 180km (on ZaïAngo profile 3). The post-salt sediment series are well known, based on seismic profiles from the oil industry. Below the base of the Aptian salt, a layered seismic unit, 1 to 2 s (twt) - 2 to 4km - thick is present. To the west, this seismic unit is difficult to image (reflectors are hardly visible), due to the salt screen. To the east, the reflectors (already seen in Zone II) are parallel to the base of the salt. Below this layered unit, a transparent, unit, about 2 s (twt) - 3 to 10km - thick, is present. Below this crustal unit, highly energetic reflectors are visible in the eastern part of the transitional domain, at a depth between about 9 and 10 s (twt) - 15 to 25km depth -; in the western part of the section, these reflectors cannot be imaged, due to the salt cover that prevents the propagation of seismic waves.

In Zone III, as in Zone II, the major observation from the MCS sections concerns the geometry of the pre-salt sediment layers (**Figures 7**, **8 & 9**).

- The layering is flat, parallel to the base of the salt, over distances greater than 100km (between shot points 500 and 1400 on profile 3).
- We do not observe any fan shaped reflector series, comparable to those documented on the Galicia Margin (e.g. Boillot *et al*, 1988), nor any significant offset in the sediment layering that could support the existence of significant extensional tectonic motions (extensional faulting, if it occurred, should have deformed the sediment cover). The deformation observed on Profile 14 (between SP 300 and SP 400,

reflectors are continuous, but not flat in the time section, **Figure 9**) could actually well be related to sedimentary processes (shale mass or diapirs) as inferred by Teisserenc & Villemin (1990, see figure 32) on the Gabon Margin.

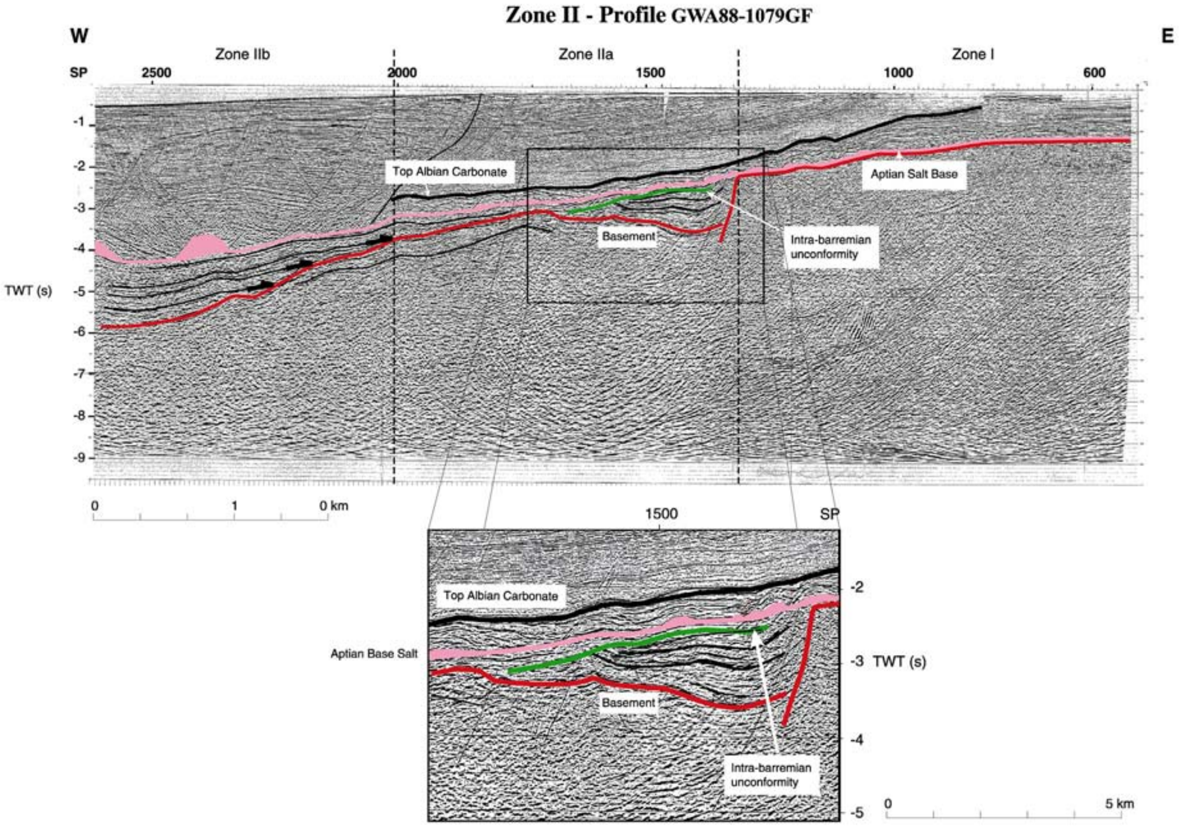

Figure 7: Industrial seismic line GWA88-1079GF (courtesy of WesternGeco) located in the continuation of ZaïAngo profile 3, below the continental shelf (zones I, II). Thin line drawings are based on *Total's* preliminary interpretation; re-interpreted line drawings (this study) are indicated by bold lines: basement is in red; base salt is in pink; the upper black, bold line indicates the top of Albian carbonates. Only one tilted block is documented (zoom in inset), in the upper part of the slope. Its activity is sealed by an unconformity (supposedly Intra-Barremian) indicated by the bold, green line. To the west of Shot Point 2000, the pre-salt sediment series (syn-rift) are characterised by reflectors parallel to the salt base that onlap on the basement (see black, bold arrows onlapping on the red line). Stippled vertical lines document the boundary between the zones. SP = shot point.

Zone IV (the ocean crust domain, related to seafloor spreading), is only sampled by ZaïAngo lines 3, 7+11, 12, 13 and 14. Due to the salt screen, the limit of this zone is mainly given by the refraction study (Contrucci *et al*, 2004). The upper sediment layers are characterized by a chaotic facies. Below what could be the base of the Oligocene (Seranne *et al.*, 1992; Anka & Séranne, 2004), the sediment layers are flat and undisturbed, onlapping on the ocean crust basement. The crust presents typical oceanic velocities (Contrucci *et al.*, 2004). The basement (top of the ocean crust) in Zone IV is highly reflective, rough, and characterized by an important relief (> 1 s twt), generating reflections of variable amplitude. This rough reflector is visible even through the salt screen, and disappears at the boundary of the presumed oceanic crust given by the refraction study. The ocean crust is about 2 s (twt) - 7km - thick. Its base is clearly present on ZaïAngo Profile 3, but hardly visible on Profiles 7-11 and 14. On Profile 3, an intra-oceanic event cutting throughout the ocean crust is observed (**Figure 5**: shotpoint 1300). This event is comparable to those documented on the Iberia Margin (Pickup *et al.*, 1996).

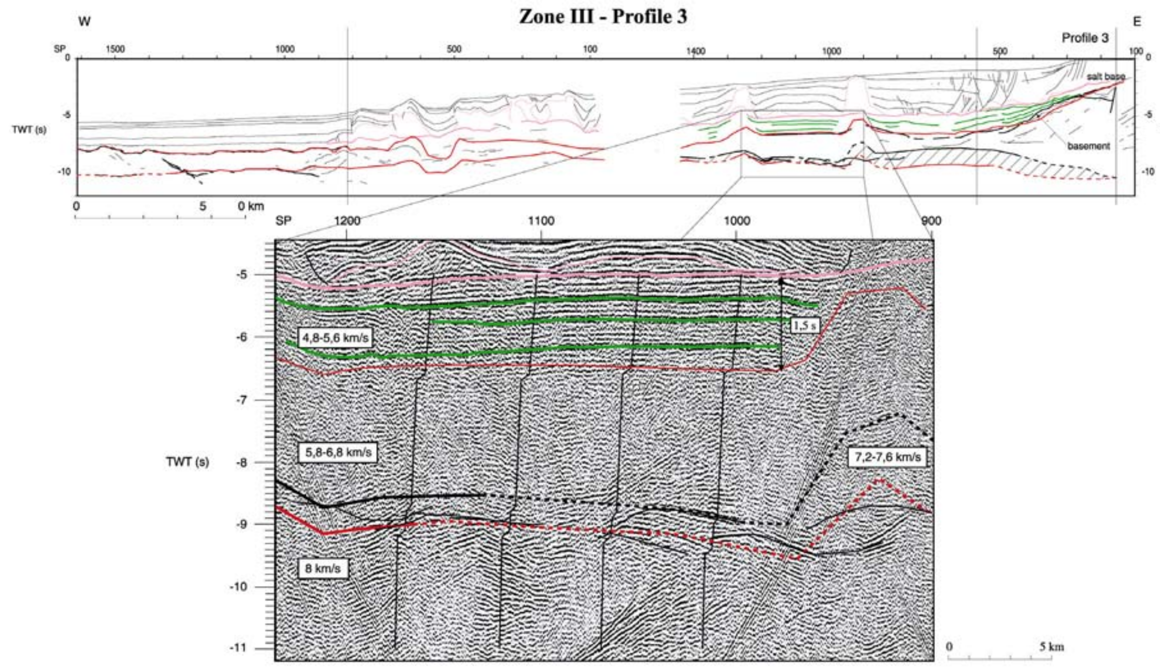

Figure 8

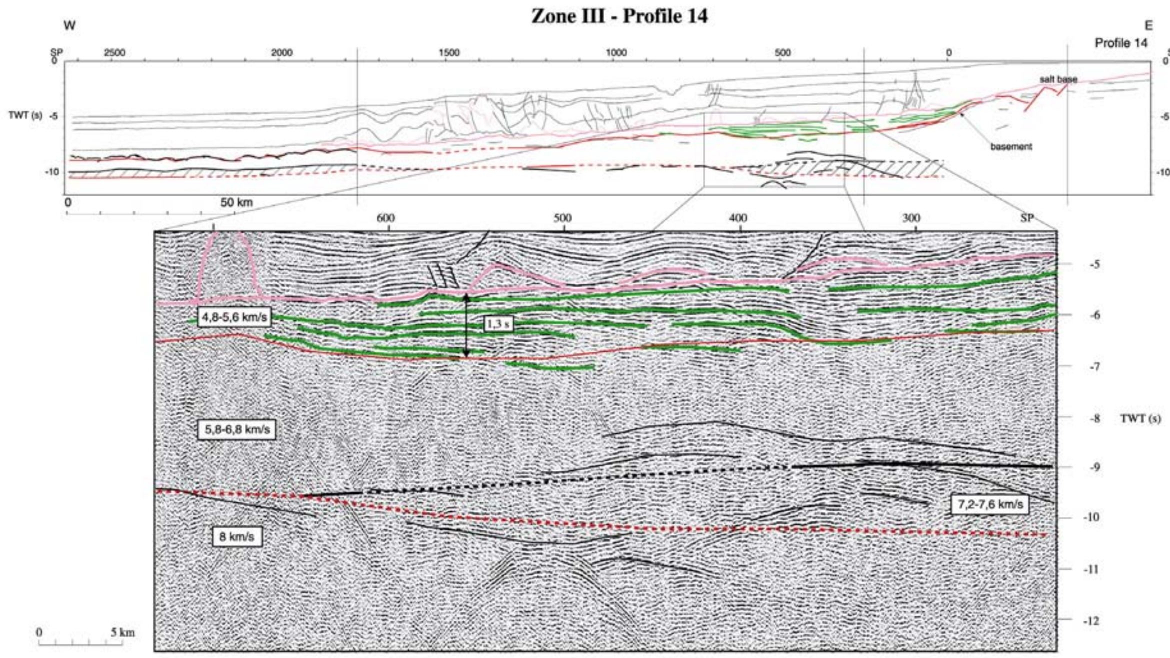

Figure 9

Figures 8 & 9: Zooms showing details for ZaïAngo profiles 3 (8) and 14 (9). The localisation of these zooms is shown on the line drawing about. Salt is in pink, the pre-salt sediment in green and the post-salt sediments and basement in the slope in black. The velocity model is superimposed in red for the basement and the Moho and in black for the top of the anomalous velocity layer (hatchured area. See text for more explanations). The Moho based on refraction is in dotted red line. The pull-up of the Moho and the basement of the anomalous velocity layer (between 850 and 950 SP) is due to the presence of a salt diapir above. SP = shot point.

At this stage, it is of major importance to note that salt is present from the continental platform to the boundary of the presumed oceanic crust, confirming the interpretation of Marton *et al.* (2000), and that the characteristics of the salt cover are different, from east to west (**Figure 10**). In the continental platform (zone I) and in the region of crustal thinning (zone II), no salt diapirs are observed. Instead, salt tectonics is characterized by i) distension structures: turtle shaped structures, listric faults associated with gravity salt tectonics that affect either the whole drift sedimentary series, or the lower series, pre-Oligocene; ii) in the eastern half of the basin, salt diapirs, spaced by more than about 20km, are present, but there is no specific signature imprinted in the bathymetry; iii) in the western part of the basin and at the boundary between zones III and IV, an accumulation of diapirs define the "salt compressive front" that clearly affects the bathymetry and the seafloor morphology. The salt compressive front forms a step in the seafloor relief, at the presumed oceanic boundary (**Figure 5**). It is also difficult to see any acoustic facies below this sub-zone.

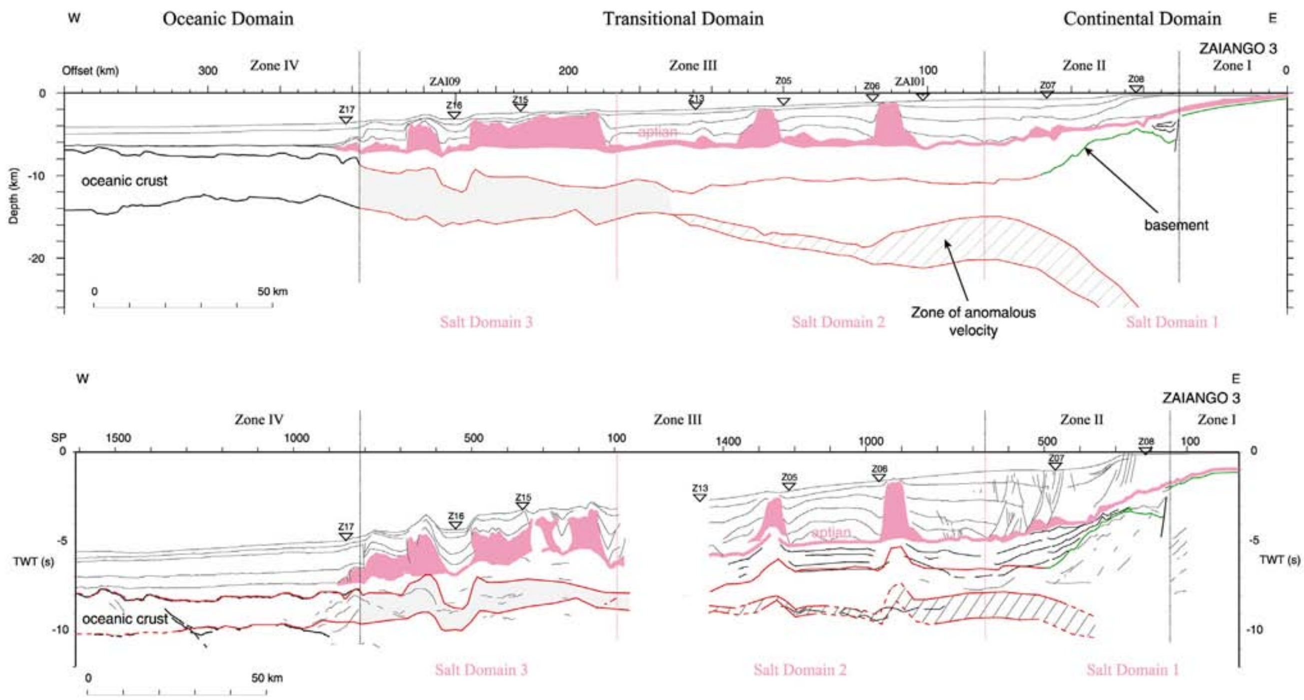

Figure 10: ZaïAngo profile 3 (in s twt) and the transformation in depth. The red lines indicate the velocity model (basement, anomalous velocity layer. and Moho) based on the interpretation of the OBS data (Contrucci *et al*, 2004). The green line indicates the basement documented on the interpretation of the MCS profiles. Salt is in pink. Three distinct salt domains are observed: i) domain 1 is the extensive salt domain; ii) domain 2 is the intermediaire salt domes domain; iii) domain 3 is the salt compressive. Note that the salt is present onshore, in platform and all the basin, without contemporaneous erosion. SP = shot point.

7 Refraction data

OBSs and land stations data provide informations about seismic velocities and the geometry of the deep structures of the margin. Based on Contrucci *et al.* (2004), we can distinguish, vertically (**Figure 11**):

- In zones I, II and III, the post-salt sediment layers are characterized by seismic velocities (based on the OBS refraction data) lower than 5 km/s, except for the Albian (112.2-98.9 Ma according to the Cenozoic time table of Berggren *et al.*, 1995) carbonates and salt layers, the velocities of which are above 5 km/s.

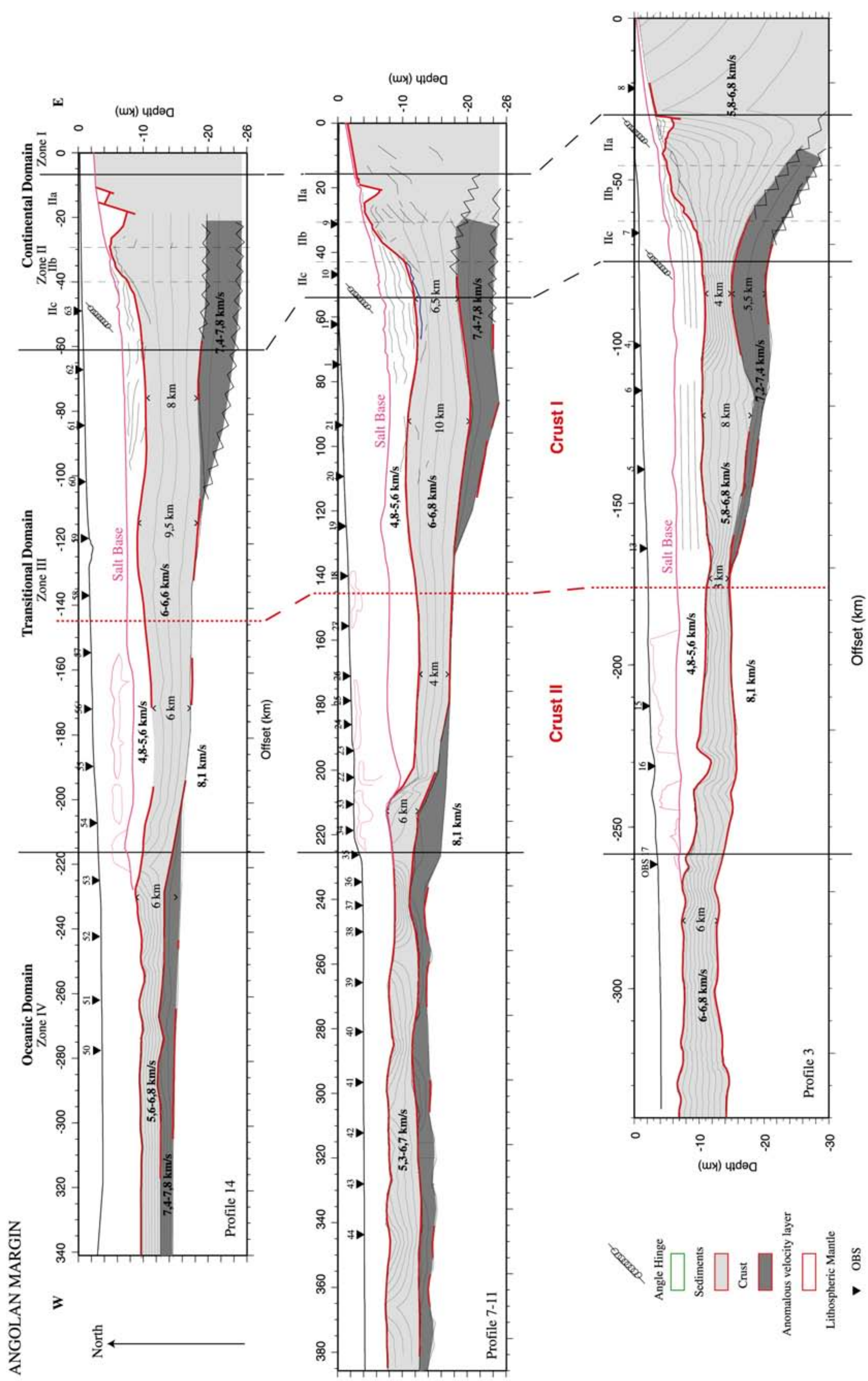

Figure 11: Synthesis of main results, based on refraction, MCS and gravity data. Black and green lines are based on the interpretation of ZaïAngo data; blue lines, on the interpretation of the industrial lines; red lines indicate the velocity interfaces, based on the interpretation of the OBS data, delineating the top of the crust, the top of the anomalous velocity zone and the Moho discontinuity (Contrucci *et*

al., 2004). Dotted red lines indicate zones that have not been sampled by seismic rays. The zigzag lines correspond to the gravity model. The pink lines (dotted or not) indicate the salt layer and the salt diapirs. The different structural domains and the zone I to IV, are separated by the black, vertical lines. Vertical black ticks indicate the boundary between the two types of crust in the transitional domain documented, by the refraction seismic. The seismic characteristics of the layers (thickness, velocities, iso-velocity curves) are indicated.

• Below the salt, the layered unit observed in the MCS sections in zones II and III is characterized by seismic velocities ranging between 4.7 and 5.6 km/s. On the basis of drill holes (in the proximal basin) and its characteristic "onlap" shape, this unit is thought to be pre-salt sediments of maximum thickness of 4km. Sediments with comparable velocities are documented elsewhere, as for instance, in the Western Mediterranean (Pascal *et al.*, 1993), or in the Orphan basin (North Atlantic Ocean) (Chian *et al.*, 2001).

• Below the pre-salt sediment layer in zones II and III, the transparent unit observed in the MCS sections is characterized by seismic velocities ranging between 5.8 km/s (at the top) and 6.8 km/s (at the bottom). This layer is thus interpreted as a crustal layer. Its thickness decreases abruptly in zone II, over a distance of less than 50km, from 30-40km (based on gravity data and also on land stations data, L. Matias (*pers. comm.*)) below the continental platform to less than 5km (on Profile 3) at the slope foot. On the western part of the pre-salt sediment basin, the layer thins regularly, from a maximum thickness of 6km (on Profile 3) to 10km (on Profile 7-11) below the post-salt sediment depot-center to a thickness of 3 to 4km below the western termination of the basin. The transitional domain is bounded to the west by a basement ridge that is clearly documented on profiles 7+11 and 14. This basement ridge is located below the western end of the salt compressive front. It is associated with a positive gravimetric anomaly and high seismic velocities (6.6 to 6.8 km/s). On profile 3 and 12, the basement high is not documented, but this may be due to the OBS distribution.

• Below this crustal layer, anomalous velocity layers (7.2 to 7.8 km/s – lower than mantle velocities, higher than continental ones) are documented, but not ubiquitously: i) on the eastern side of the basin and below zone II (where crustal thinning mostly occurs), a layer, up to 4 to 6km thick, with velocities ranging between 7.2 and 7.6 km/s, is visible on all profiles. Its maximum thickness occurs where the basin reaches its maximum depth and where the crustal layer reaches its minimum thickness; ii) to the west, a high velocity layer, less than 2km thick, with velocities between 7.4 and 7.8 km/s, is also present at the boundary between the transitional and oceanic domains (on profile 7-11, below the basement ridge) and below the oceanic crust. However, this layer is only seen on profiles 14 and "7+11". The absence of such a layer on profile 3 could be due to a main structural difference of the portion of the margin sampled by this profile (northern part of Kwanza basin), or due to a less dense OBS spacing (compared to profiles 14 or 7+11). Although they have comparable P-wave velocity ranges (7.2 - 7.6 km/s and 7.4 - 7.8 km/s), these layers have probably not the same significance: following Contrucci *et al.*, (2004), we infer that the layer below the eastern part of the basin and below the region of maximum crustal thinning is related to rifting processes, meanwhile the western one is related to crustal accretion processes.

It must be pointed out that the transitional domain appears to be divided into two sub-basins, separated by a smooth basement high. Its seismic structure also varies, from east to west. Two types of crust are suggested by the refraction data (**Figure 11**): "Type I" crust is found in the eastern part of the basin. It is characterized by an upper layer of thickness greater than 5km (average thickness is 5.5km on profile 3; about 8km on profile "7+11"; 8.5km on profile 14), lying over an anomalous velocity layer (7.2 – 7.6 km/s), up to 6km thick; "Type II" crust is found in the western part of the basin. Due to the salt screen, there is no MCS image of the structures below the salt diapirs and "Type II" crust is only defined based on OBS data. Its thickness (generally less than 5km) decreases from east to west. Clearly, there is no anomalous velocity layer at its base, except near its western termination, where a basement ridge and a thin (2km) high velocity layer (7.4 to 7.8 km/s) are documented on the two profiles having denser OBS spacing (14 and "7+11"). At this stage, it is important to note that "Type II" crust coincides with the "salt compressive front", an area characterized by an accumulation of numerous, closely spaced salt diapirs, which clearly imprint the seafloor morphology.

8 Discussion and conclusion

On the basis of this study on MCS, OBS (Contrucci *et al*., 2004), landstations and gravity data, we can conclude that:

- The seismic structure of the Angolan margin is very different from the one found at volcanic margins, suggesting that volcanism is not a major process for the formation of the margin. The MCS data do not indicate the presence of clearly defined seaward dipping reflectors (SDR) similar to those observed at recognized volcanic margins, such as the Norwegian margin (e.g. Eldholm *et al.,* 1989), the Greenland margin (e. g. Korenaga *et al.,* 2000), the US East Coast margin (e. g. Holbrook & Kelemen, 1993), the Aden margin (Tard *et al*, 1991) or the Namibia margin (Bauer *et al.,* 2000; Austin & Uchupi, 1982). Some authors have proposed that SDRs were present on the South Gabon margin (e. g. Jackson *et al*., 2000), and on the conjugated Brazilian margin, in the Sergipe-Alagoas basin (Mohriak *et al*., 1995), suggesting that the central segment of the South Atlantic African margins could also be volcanic. However, all seismic images from this central segment are very different from the images obtained on the well studied volcanic margins listed above (**Figure 12**): on the Greenland margin (Korenaga *et al.,* 2000), for instance, the 4km thick SDRs layer lies on top of a 30km-thick igneous crust and extends over a lateral distance of 150km; in contrast, the SDR layers on the Sergipe-Alagoas margin extends over less than 20km and its maximum thickness is less than 1 s (twt) - about less than 3km - (Mohriak *et al.*, 1995). If their thickness is similar, their lateral extensions are quite different and the same genetic process can hardly be attributed to both structures. Based on refraction data, the seismic structure (seismic velocities and thicknesses) of the Angola margin also appears to be very different from the one obtained at volcanic margins (Contrucci *et al.*, 2004): volcanism is likely to have occurred (traces of volcanism are probably present, as reported by Jackson *et al.* (2000) for the South Gabon margin) but it is not a major process for the formation of the margin. The thermal conditions that finally resulted in crustal thinning did not produce massive volcanic sequences.
- Crustal thinning is very abrupt and occurs mostly below the continental slope: crustal thickness decreases from more than 30km to about 5km (on Profile 3), over a lateral distance of less than 50km (as for instance in the Gulf of Biscay: Thinon (1999); Thinon *et al* (2003)). Only few tilted blocks are observed on the available reflection seismic data (one or two, depending on the profile), found only on the upper shallower part of the slope (zone II). Their tectonic episode is apparently sealed by a surface of unconformity prior to salt deposition. If present, tilted blocks at the slope foot or in the deepest part of the basin are necessarily of limited size, i.e. too small to be visible on the MCS sections. No imprint of significant extension is observed to explain this crustal abrupt thinning.
- The Angolan Margin is characterized by the existence of a 200km-large and less than 10 km-thick basin. In this transitional domain, the crust cannot be recognized as oceanic, nor as continental. The MCS data also indicate that sub-Aptian salt sediment infill is flatly layered: reflectors within the sub-salt basin are mostly parallel to the salt cover and to the basement. The pre-salt sediments are thus not affected by any deformation that would imply significant horizontal motions (if crustal thinning had occurred by horizontal stretching, the sediment infill would show a fan-shaped layering) and their deposition occurred while the basin was subsiding vertically without any flexure.

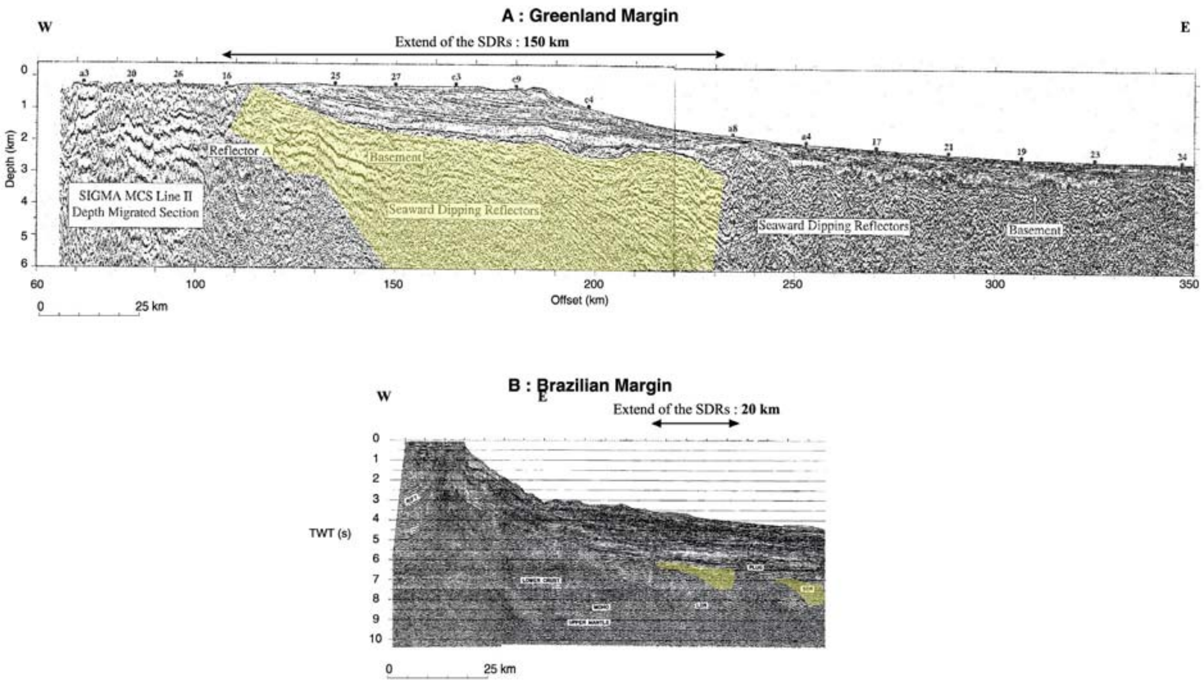

Figure 12: Comparison between two continental margins (Brazilian Margin and Greenland volcanic margin). Low energy reflectors interpreted as SDRs on the Brazilian profile (Morhiak *et al*., 1995) and the 4 km thick SDR layer on the Greenland profile (Korenaga *et al*., 2000) are underlined in yellow. Note the difference of extension (20km versus 150km).

- Salt was deposited during the Aptian time on the platform and all over the transitional domain (zone III). The salt cover is continuous (this is particularly clear on industrial profiles), from the continental shelf to the western boundary of the basin (**Figure 10**), refuting the hypothesis of two different salt formations (Karner *et al.* (1997)) and confirming the interpretation of Marton *et al.* (2000), now accepted by Karner (2004). Following Jackson *et al.* (2000), the geochemical difference between salt on the platform and salt in the deep basin could be explained, by petrological differences in the underlying substratum.
- On the shelf, pre-salt sediments mostly vary from continental to lacustrine. The earliest marine sediment layer (known as the “La Chela” layer in the stratigraphic column) is thin and was deposited immediately prior the Aptian salt layer: there is no thick, significant marine sequence pre-dating the salt deposition (Brognon & Verrier, 1966; Masson, 1972; Brice *et al*., 1982; Giresse, 1982). This situation is very different from what is observed for the Western Mediterranean basin, one of the best known confined basins in the world. In that case, a marine basin (of unknown depth) existed before salt deposition: marine sediments were deposited prior to Messinian times (7.1-5.3 Ma, according to the time table of Berggren *et al.,* 1995), as seawater circulated in open conditions between the Mediterranean and the Atlantic Ocean. At Messinian times, seawater circulation stopped, due to the closure of the Gibraltar Strait, causing, by evaporation, the lowering of the sea level and the erosion of both the platform and the emerged parts of the continental slope. This example clearly shows that salt deposition in confined environmental conditions almost always is associated with erosion surfaces. On the Angola margin, salt is found continuously from the deep actual basin (the sag) to the unthinned continental platform (that is: almost not affected by subsidence). Because salt deposit occurs in a horizontal context, this observation proves that the top of the salt was deposited in very shallow environment (at the same depth as the unthinned continental platform). Moreover, if the salt was deposed in a confined deep basin, as in Mediterranean Sea, large pre-salt marine sediments layer and erosion on the continental slope should be observed.

Together with the absence of thick marine layers prior to Aptian times, the absence of an erosion surface contemporaneous with salt deposition indicate that salt was not deposited in a context of active marine sedimentation, but is related to the first marine transgression in the basin. These crucial observations **imply shallow deposition environments during the rifting**.

- As we have shown, the sag basin does not exhibit the characteristics of brittle deformation and the geometry of the pre-salt sediment indicates that their deposition occurred while the basin was subsiding vertically without any flexure (**Figure 13**).

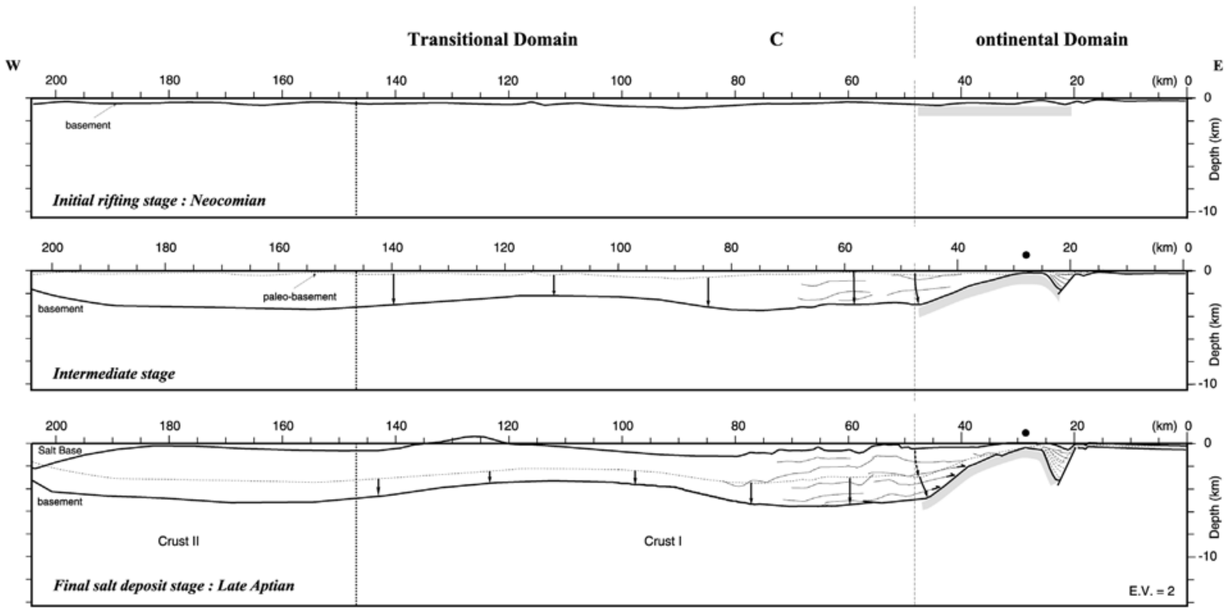

Figure 13 : Pre-break-up tectonic evolution of the Angolan margin on the basis of profile Zaiango 7, from Neocomian (144,2 Ma) to Late Aptien (112,2 Ma). The black line corresponds to the basement; dotted lines represent the paleo-basement of the precedent stage. The motion in the continental domain may be assimilated to a rotation (grey zone and curved arrows; the black dot indicates approximately the center of rotation), whereas in the transitional domain, the motion is quasi-vertical (vertical arrows). This picture shows the different behaviour pattern between the continental and the transitional domain (marked by the stippled vertical lines).

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The about-zero level salt layer deposition constrains the paleo-geometry of the margin at Barremian times, prior to the salt sequence, which becomes an important reference marker to reconstruct the initial evolution of the margin. The carbonate series which followed salt deposition provides an indication of the basin subsidence: before the carbonate deposition, the subsidence is approximately equal to salt sedimentation rate, allowing salt to be deposited at near-zero water depths. The subsidence then increased, thereby ending the salt deposition phase. The structures of the ante-salt and post–salt layers in the "sag basin" therefore show only vertical motion of the substratum. Last but not least, the precise kinematic reconstruction allows very little horizontal motions during the formation of this margin (Moulin, 2003; Moulin *et al.,* in preparation). The basin thus appears to have been mainly formed vertically: vertical motions prevail compared to horizontal motions. This excludes any stretching processes and points to either inherited very thin continental crust or more likely to lower crust thinning processes. The transitional crust seems to be divided into two parts, called "Type I" crust and "Type II" crust. If "Type I" crust is probably made by the upper continental crust, "Type II" crust could be an atypic oceanic crust, serpentized mantle, lower continental crust, intruded continental crust. In the actual state of the art, it is hard to decipher between the different hypothesis without information on the deep structure of the homologous continental margin. Driscoll and Karner (1998) have suggested a decoupling zone between 1) an upper crust and 2) ductile-deforming lower crust and lithospheric mantle. In the Campos Basin, slightly south to the exact homologous margin of ZaiAngo, the compilation of a published profile (Mohriak *et al.,* 1990) and an industrial profile (Total), exhibits an slightly smaller, analogous structuration than the ZaiAngo margin. Following Séranne *et al*. (1995) and Séranne (1999) for the NW-Mediterranean basin, it seems to us that the hypothesis of the existence of a detachment exhuming lower crust ("Type II" crust) from beneath the continental margin and exposing it in the deep basin is a good candidate to explain the structuration of the Angola margin. All the observations reported here will have to be accounted for by any future model describing the formation of West African and Brazilian margins.

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References

Abreu, V. S., (1998). Geologic evolution of conjugate volcanic passive margins : Walvis (Africa) and Pelotas (South America) Basins. Ph.D. dissertation, *Rice University*, Houston, Texas, 355 pp.

Anka, Z. & Séranne, M., (2004). Reconnaissance study of the ancient Zaire (Congo) deep-sea fan. (ZaiAngo Project). *Marine Geology*, **209**, 1-4: 223-244.

Austin, J. A. & Uchupi, E., (1982). Continental-oceanic crustal transition off Southwest Africa. *American Association of Petroleum Geologists Bulletin*, **66** : 1328-1347.

Avedik, F., Renard, V., Allenou, J.-P. & Morvan, B., (1993). « Single bubble » air-gun array for deep exploration. *Geophysics*, **58**; 3 : 366-382.

Bauer, K., Neben, S., Schreckenberger, B., Emmermann, R., Hinz, K., Fechner, N., Gohl, K., Schulze, A., Trumbull, R.B. & Weber, K., (2000). Deep structure of the Namibia continental margin as derived from integrated geophysical studies. *Journal of Geophysical Research*, **105** : 25829-25853.

Berggren, W. A., Kent, D. V., Swisher, C. C. & Aubry, M.-P., (1995). A revised Cenozoic geochronology and chronostratigraphy. In Berggren, W. A., Kent, D. V. & Hardenbol, J. (editors). Geochronology, Time Scales and Global Stratigraphic Correlation, A Unified Temporal Framework for an Historical Geology. *Spec. Publ. Soc. Econ. Paleontol. Mineral*., Tulsa, **54** : 129-212.

Boillot, G., Girardeau, J. & Kornprobst, J., (1988). Rifting of the Galicia margin: crustal thinning and emplacement of mantke rocks on the seafloor. *Proc. ODP, Sci. Results*, 103, College Station, TX, 741-756.

Bond, G., (1978). Evidence for Late Tertiary uplift of Africa relative to North America, South America, Australia and Europe. *Journal of Geology*, **86** : 47-65.

Brice, S. E., Cochran, M. D., Pardo, G. & Edwards, A. D., (1982). Tectonics and sedimentation of the South Atlantic Rift Sequence : Cabinda, Angola. In J.S. Watkins & C.L. Drake (editors). Studies in Continental Margin Geology, *American Association of Petroleum Geologists Memoir* **34**, Tulsa : 5-18.

Brognon, G. P. & Verrier, G. V., (1966). Oil and geology in Kwanza basin of Angola. *American Association of Petroleum Geologists Bulletin*, **50** : 108-158.

Burke, K. & Dewey, J.F., (1974). Two plates in Africa during the Cretaceous? *Nature*, **249** : 313-316.

Burke, K., (1996). The African Plate. *South African Journal of Geology*, **99** : 341-409.

Cande, S. C. & Rabinowitz, P. D., (1977). Magnetic Anomalies on the Continental Margin of Brazil. *Am. Assoc. Pet. Geol*.. Tulsa, OK, United States, 1 map.

Castro, A. C. M. Jr., (1987). The northeastern Brazil and Gabon basins; a double rifting system associated with multiple crustal detachment surfaces. *Tectonics*. **6**, 6 : 727-738.

Chian, D., Reid, I. D. & Jackson, H. R., (2001). Crustal structure beneath Orphan Basin and implications for nonvolcanic continental rifting. *Journal of Geophysical Research*, **106**, 6 : 10,923-10,940.

Choubert, G., Faure-Muret, A. & Sougy, J., (1968). Carte Tectonique Internationale de l'Afrique, *UNESCO*, 9 cartes.

Contrucci, I., Matias, L, Moulin, M., Géli, L., Klingelhoeffer, F., Nouzé, H., Aslanian, D., Olivet, J.-L., Sibuet, J.-C. & Réhault, J.-P., (2004). Deep structure of the West African continental margin, between 5°S and 8°S, from reflection / refraction seismics and gravity data, *Geophysical Journal International*, **158** : 529-553.

Cramez, C. & Jackson, M. P. A., (2000). Superposed deformation straddling the continental-oceanic transition in deep-water Angola. *Marine and Petroleum Geology*, **17** : 1095-1109.

Curie, D., (1984). Ouverture de l'Atlantique sud et discontinuités intra-plaque : une nouvelle analyse. Ph. D thesis, *Univ. de Bretagne Occidentale*, Brest, 192 pp.

Davison, I., (1999). Tectonics and hydrocarbon distribution along the Brazilian South Atlantic margin. In : Cameron, N. R., Bate R. H. & Clure, V. S., (editors), The oil and gas habitats of the South Atlantic, *Geol. Soc. London, Spec. Publ.*, **153** : 133-151.

Doyle, J.A., Biens, P., Doerenkamp, A. & Jardiné, S., (1977). Angiosperm pollen from the Pre-Albian Lower Cretaceous of equatorial Africa. *Bulletin des Centres de Recherche et d'Exploration-Production de Elf-Aquitaine*, **1** : 451-473.

Doyle, J.A., Jardiné, S. & Doerenkamp, A., (1982). Afropolis, un nouveau genre de pollen d'Angiosperme précoce, avec de données sur la palynostratigraphie et les paléoenvironnements du Crétacé du Nord-Gondwana. *Bulletin des Centres de Recherche et d'Exploration-Production de Elf-Aquitaine*, **6** : 39-117.

Driscoll, N.. W. & Karner, G. D., (1998). Lower crustal extension across the Northern Carnarvon basin, Australia: Evidence for an eastward dipping detachement. *Journal of Geophysical Research*, **103**, 3 : 4975-4991.

Dupré, S., Bertotti, G. & Cloetingh, S., (2003). South Gabon Margin: tectonic evolution, basin configuration and characteristics of rifting process inferred from multi-data analysis, gravity and forward lithospheric thinning modelling. *EGS, AGU*, *EUG Meeting*, 6-11 April, Nice.

Dupré, S. (2003). Integrated tectonic study of the South Gabon Margin: Insights on the rifting style from seismic, well and gravity data analysis and numerical modelling, Ph. D Thesis, *Vrije University*, Amsterdam, 125 pp.

Duval, B., Cramez, C., & Fonck, J.-M., (1992). Rafts tectonics in the Kwanza Basin, Angola. *Marine and Petroleum Geology*, **9**: 389-404.

Eldholm, O., Thiede, J. & Taylor, E. (1989). The Norwegian continental margin; tectonic, volcanic, and paleoenvironmental framework. In: Eldholm, O., Thiede, J., Taylor, E., Barton, C., Bjorklund, K. R., Bleil, U., Ciesielski, P., F., Desprairies, A., Donnally D. M., Froget, C., Goll, R., Henrich, R., Jansen, E., Krissek L. A., Kvenvolden, K. A., LeHuray, A. P., Love, D. A., Lysne, P., McDonald, T. J., Mudie, P. J., Osterman, L. E., Parson, L. M., Phillips, J. D., Pittenger, A., Qvale, G., Schoenharting, G., Viereck, L., Winkler, W. R., (editors). Proceedings of the Ocean Drilling Program, Norwegian Sea; covering Leg 104 of the cruises of the Drilling Vessel JOIDES Resolution, Bremerhaven, Germany, to St. John's. *Proceedings of the Ocean Drilling Program, Scientific Results*. **104** : 5-26.

Emery, K.O., Uchupi, E., Phillips, J., Bowin, C. & Mascle, J., (1975). Continental Margin off Western Africa : Angola to Sierra Leona. *American Association of Petroleum Geologists Bulletin*, **59** : 2209-2265.

Evans, R., (1978). Origin and signifiance of evaporites in basins around Atlantic margin *American Association of Petroleum Geologists Bulletin,* **62** : 223-234.

Ewing, J. R., Leyden, R. & Ewing, M., (1969). Refraction shooting with expendable sonobuoys. *American Association of Petroleum Geologists Bulletin*, **53** , 1 : 174-181.

Fairhead, J.D., (1988). Mesozoic plate tectonic reconstructions of the central South Atlantic Ocean : The role of the West and Central African rift system. *Tectonophysics*, **155** : 181-191.

Fonck, J.-M., Cramez, C. & Jackson, M. P. A., (1998). Role of the subaerial volcanic rocks and major unconformities in the creation of South Atlantic margins. In *Am. Assoc. Petrol. Geol. International Conference Extended Abstracts Volume*, Rio de Janeiro, Brazil, November : 38-39.

Giresse, P., (1982). La succession des sédimentations dans les bassins marins et continentaux du Congo depuis le début du Mésozoïque. *Sci. Géol. Bull.*, **35**, 4 : 183-206.

Gomes, P. O., Gomes, B. S., Palma, J. J. C., Jinno, K. & de Souza, J. M., (2000). Ocean-Continent Transition and Tetctonic Framework of the Oceanic Crust at the Continental Margin off NE Brazil : Results of LEPLAC Project. In W. Mohriak & M. Talwani, Atlantic Rifts and

Continental Margins, *American geophysical Union*, **115** : 261-291.

Gradstein, F.M., Agterberg, F.P., Ogg, J.G., Hardenbol, J. Van Veen, P., Thierry, J. & Huang, Z., (1994). A Mesozoic time scale. *Journal of Geophysical Research*, **99** : 24051-24074.

Guardado, L. R., Gambo, L. A. P. & Lucchesi, C. F., (1989). Petroleum geology of the Campos Basin, a model for a producing Atlantic-type basin. In : Edwards, J. D. & Santogrossi, P. A. (editors), Divergent/passive margins basins, *American Association of Petroleum Geologists Memoir*, **48** : 3-79.

Guiraud, R. & Maurin, J.C., (1992). Early Cretaceous rifts of Western and Central Africa : an overview. *Tectonophysics*, **213** : 153-168.

Haq, B.U., Hardenbol, J. & Vail, P.R., (1987). Chronology of fluctuating sea level since the Triassic (250 million years ago to Present). *Science*, **235** : 1156-1167.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. & Smith, D. G., (1990). A Geologic Time Scale. *Ed. Cambridge Univ. Press*, New-York, 265 pp.

Hinz, K., Neben, S., Schreckenberger, B., Roeser, H. A., Block, M., Goncalves de Souza, K. & Meyer, H., (1999). The Argentine continental margin north of 48 degrees S; sedimentary successions, volcanic activity during breakup. *Marine and Petroleum Geology*, **16**, 1 : 1-25.

Hoolbrok, W. S. & Kelemen, P. B., (1993). Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup. *Nature*, **364** :433-436.

Jackson, M. P. A., Cramez, C. & Fonck, J.-M., (2000). Role of subaerial volcanic rocks and mantle plumes in creation of South Atlantic margins : implications for salt tectonics and source rocks. *Marine and Petroleum Geology*, **17** : 477-498.

Karner, G. D., Driscoll, N. W., McGinnis, J. P., Brumbaugh, W. D. & Cameron, N. R., (1997). Tectonic significance of syn-rift sediment packages across the Gabon-Cabinda continental margin. *Marine and Petroleum Geology*, **14** : 973-1000.

Karner, G. D. & Driscoll, N. W., (1999). Tectonic and stratigraphic development of the West African and eastern Brazilian Margins : insights from quantitative basin modelling. In : Cameron, N. R., Bate R. H. & Clure, V. S., (editors), The oil and gas habitats of the South Atlantic, *Geol. Soc. London, Spec. Publ*., **153** : 11-40.

Karner, G.D., (2004). Structural and depositionnal style of the syn-rift systems of the West African and Brazillian cotinental margins: Regional subsidence independent of brittle deformation, *Eos Trans. A.G.U*., **85**, 17, Jt. Assem. Suppl.

Klitgord, K. & Schouten, H., (1986). Plate kinematics of the Central Atlantic. In : Vogt P.R. & Tucholke B.E. (Editors). The Geology of North America, vol. **M** : The Western North Atlantic Region. *Geological Society of America*, Boulder, CO, 351-378.

Korenaga, J., Holbroock, W. S., Kent, G. M., Kelemen, P. B., Detrick, R. S., Larsen, H. C., Hopper, J. R. & Dahl-Jensen, T., (2000). Crustal structure of the southeast Greenland margin from joint refraction and reflection seismic tomography. *Journal of Geophysical Research*, **105** : 21591-21614.

Kowsmann, R., Leyden, R. & Francisconi O., (1977). Marine Seismic Investigations, Southern Brazil Margin. *American Association of Petroleum Geologists Bulletin*, **61** : 546-557.

Lehner, P. & De Ruiter, P. A. C., (1977). Structural history of Atlantic margin of Africa. *American Association of Petroleum Geologists Bulletin*, **61**, 961-981.

Leyden, R., Ludwing, W. J. & Ewing, M., (1971). Structure of Continental Margin off Punta del Este, Uruguay, and Rio de Janeiro, Brazil. *American Association of Petroleum Geologists Bulletin*, **55**, 12 : 2161-2173.

Leyden, R., (1976). Salt distribution and crustal models for the eastern Brazilian margin. *An. Acad. Bras. Cienc*., **48** : 159-168.

Lucazeau, F., Brigaud, F. & Leturmy, P., (2003). Dynamic interactions between the Gulf of Guinea passive margin and the Congo River drainage basin. 2: Isostasy and uplift. *Journal of Geophysical Research*., **108** (B8), 2384, doi:10.1029/2002JB001928.

Lunde, G., Aubert, K., Lauritzen, O. & Lorange, E., (1992). Tertiary Uplift of the Kwanza Basin in Angola. In : Curneller (Editor), *Géologie Africaine-Compte Rendu des colloques de Géologie de Libreville*. Centre de Recherche et d'Exploration Production, Elf Aquitaine : 6-8.

Marton, G., L, Tari, G. C. & Lehmann C. T., (2000). Evolution of the Angolan Passive Margin, West Africa, with Emphasis on Post-Salt Structural Styles. In W. Mohriak & M. Talwani (editors), Atlantic Rifts and Continental Margins : *American Geophysical Union*, **115** : 129-149.

Mascle, J.& Renard, V., (1976). The marginal Sao Paulo Plateau, comparison with the southern Angolan margin. In: de-Almeida-F. F. M. (editor), Simposio internacional sobre as margens continentais de tipo atlantico. *Anais da Academia Brasileira de Ciencias.* **48**; Suplemento 179-190.

Masson, M.P., (1972). L'exploration pétrolière en Angola. *Pétrole et Techniques*. **212** : 21-40.

Mohriak, W. U. & Dewey, J. F., (1987). Deep seismic reflectors in the Campos Basin, offshore Brazil. In: Drummond, M. & Smith C.

(Prefacers), Deep seismic reflection profiling of the continental lithosphere. *Geophysical Journal of the Royal Astronomical Society*. **89**, 1 : 133-140.

Mohriak, W. U., Hobbs, R. & Dewey, J. F., (1990). Basin-forming processes and the deep strucutre of the Campos Basin, offshore Brazil. *Marine and Petroleum Geology*, **7** : 94-122.

Mohriak, W.U., Rabelo, J. H. L., De Matos, R. & De Barros, M. C., (1995). Deep Seismic reflection profiling of sedimentary basins offshore Brazil : Geological objectives and preliminary results in the Sergipe Basin. *Journal of Geodynamics*, **20** : 515-539.

Mohriak, W.U., Bassetto, M. & Vieira, I.S., (1998). Crustal architecture and tectonic evolution of the Sergipe-Alagoas and Jacuipe Basins, offshore northeastern Brazil. *Tectonophysics*, **288** : 199-220.

Mohriak, W.U., Mello, M.R., Bassetto, M., Vieira, I.S & Koutsoukos, E.A., (2000). Crustal Architecture, Sedimentation, ans Petroleum Systems in the Sergipe-Alagoas Basin, Northeastern Brazil. In M.R. Mello & B.J. Katz, (editors), *Petroleum systems of South Atlantic margins* : *American Association of Petroleum Geologists Memoir*, **73** : 273-300.

Moulin. M., (2003). Etude géologique et géophysique des marges continentales passives : exemple du Zaïre et de l'Angola. Ph. D Thesis, *Univ de Bretagne Occidentale*, Brest, 2 vol., 138 pp, http://www.ifremer.fr/docelec/.

Mussard, J.-M., (1996). Les palynomorphes, indicateurs des variations duniveau marin relatif : Analyses quantitatives dans l'Albian supérieur de la république du Congo. In : S. Jardiné, I. de Klasz & J.-P. Debenay (editors), Géologie de l'Afrique et de l'Atlantique Sud, Compte Rendus des Colloques de géologie d'Angers, 16-24 juillet 1994, *Mémoires du Bulletin des Centres de Recherche et d'Exploration-Production d'Elf*, **16** : 57-66.

Nürnberg, D. & Müller, R. D., (1991). The tectonic evolution of the South Atlantic from Late Jurassic to present. *Tectonophysics*, **191** : 27-53.

Odin, G. S. & Odin, C., (1990). Echelle numérique des temps géologiques. *Géochronique*, **35** : 12-21.

Ojeda, H.A., (1982). Structural framework, stratigraphy, and evolution of Brazilian marginal basins. *American Association of Petroleum Geologists Bulletin*, **66** : 732-749.

Pascal G. P., Mauffret, A. & Patriat, P., (1993). The ocean-continent boundary in the Gulf of Lion from analysis of expending spread profiles and gravity modelling. *Journal of Geophysical International*, **113** : 701-726.

Pautot, G., Renard, V., Daniel, J. & Dupont, J., (1973). Morphology, limits, origin and age of salt layer along South Atlantic African margin. *American Association of Petroleum Geologists Bulletin*, **57** : 1658-1671.

Pawlowski, R., (1999). Megaregional rift-drift structural controls on hydrocarbon accumulations offshore West Africa. *The Leading Edge*, **18** , 5 : 600-603.

Pickup, S. L. B., Whitmarsh, R. B., Fowler, C. M. R. & Reston, T. J., (1996). Insight into the nature of the ocean-continent transition off West Iberia from a deep multichannel seismic reflection profile. *Geology*, **24**, 12 : 1079-1082.

Pindell, J. & Dewey, J. F., (1982). Permo-triassic reconstruction of western pangea and the evolution of the Gulf of Mexico/Caribbean region. *Tectonics*, **1**, 2 : 179-211.

Rabinowitz, P. D. & LaBrecque, J., (1979). The Mesozoic South Atlantic Ocean and Evolution of Its Continental Margins. *Journal of Geophysical Research*, **84** : 5973-6002.

Renard, V. & Mascle, J., 1974, Eastern Atlantic continental margins; various structural and morphological types. *In*: Burk, C.-A & Drake, C.-L (Editors), The geology of continental margins (Springer-Verlag, New York, United States), 285-291.

Reyre, D., (1984). Caractères pétroliers et évolution géologique d'une marge passive. Le cas du basin bas Congo – Gabon. *Bull. Centres Rech. Explor. Prod. Elf-Aquitaine*, **8** : 303-332.

Rosendahl, B.R., Groschel-Becker, H., Meyers, J. & Kaczmarick, K., (1991). Deep seismic reflection study of a passive margin, southeastern Gulf of Guinea. *Geology*, **19** : 291-295.

Séranne, M., Séguret, M. & Fauchier, M., (1992). Seismic super-units and post-rift evolution of the continental passive margin of southern Gabon, *Bull. Soc. Geol. France*, **163**, 2 : 135-146.

Séranne, M., Benedicto, A., Truffert, C., Pascal, G. & Labaume, P., (1995). Structural style and evolution of the Gulf of lion Oligo-Miocene rifting : Role of the Pyrenean orgeny. *Marine and Petroleum Geology*, **12** : 809-820.

Séranne, M., (1999). The Gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview. In Durand, B., Jolivet, L., Horvath, F. & Séranne, M. (Editors), The Mediterranean Basins : Tertiary Extension within the Alpine Orogen, *Geological Society Special Publications. 156* : 15-36.

Tard, F., Masse, P., Walgenwitz, F. & Gruneisen, P., (1991). The volcanic passive margin in the vicinity of Aden, Yemen. *Bull. Centres Rech. Explor. Prod. Elf-Aquitaine*, **15**, 1: 1-9.

Teisserenc, P. & Villemin, J., (1990). Sedimentary Basin of Gabon—Geology and Oil Systems. In : Edwards, J. D. & Santogrossi, P. A. (Editors), Divergent/passive margins basins, *Am. Assoc. Petrol. Geol. Memoir*, 48 : 117-199.

Thinon, I., (1999). Structure profonde de la marge Nord-gascogne et du bassin Armoricain (golfe de Gascogne). Ph. D Thesis, *Univ. de Bretagne Occidentale*, Brest, 327 pp.

Thinon, I., Matias, L., Rehault, J-P., Hirn, A., Fidalgo Gonzalez, L. & Avedik, F., (2003). Deep structure of the Armorican Basin (Bay of Biscay); a review of Norgasis seismic reflection and refraction data. *Journal of the Geological Society of London*, **160**, 1 : 99-116.

Unternehr, P., Curie. D., Olivet, J.L., Goslin J. and Beuzart P., (1988). South Atlantic fits and intraplate boundaries in Africa and South America. *Tectonophysics*, **155** : 169-179.

Ussami, N., Karner, G. D. & Bott, M. H. P., (1986). Crustal detachment during South Atlantic rifting and formation of Tucano-Gabon basin system. *Nature*, **322**, 6080 : 629-632.

Vernet, R., Assoua-Wande, C., Massamba, L. & Sorriaux, P., (1996). Paléogéographie du Crétacé (Albien-Maastrichtien) du bassin côtier congolais. In : S. Jardiné, I. de Klasz & J.-P. Debenay (Editors), Géologie de l'Afrique et de l'Atlantique Sud, Compte Rendus des Colloques de géologie d'Angers, 16-24 juillet 1994, *Mémoires du Bulletin des Centres de Recherche et d'Exploration-Production de Elf*, **16** : 39-55.

Walgenwitz, F., Pagel, M., Meyer, A., Maluski, H. & Monié P., (1990). Thermo-chronological approach to reservoir diagenesis of the offshore Angola basin: a fluid inclusion, 40Ar-39Ar and K-R investigation. *American Association of Petroleum Geologists Bulletin*, **74** (5) : 547-563.

Walgenwitz, F., Richert, J.P. & Charpentier, P., (1992), Southwest border of African plate; thermal history and geodynamical implications. In : Poag, C.W. & de Graciansky, P.C. (Editors), *Geologic evolution of Atlantic continental rises*. Van Nostrand Reinhold, New-York : 20-45.

Wanesson, J., (1991). Structure and Evolution of adjoining segments of the West African Margin determined from deep seismic profiling. *Geodynamics*, **22** : 275-289.

Watts, A. B. & Stewart, J., (1998). Gravity anomalies and segmentation of the continental margin offshore West Africa. *Earth and Planetary Sciences Letters*, **156** : 239-252.

Wessel, P. & Smith, W.H.F., (1995). A new version of the Generic Mapping Tools (GMT), *EOS, Trans. Am. Geophys. Un*., **76**, 329.

Wilson, P. G., Turner, J. P. & Westbrook, G. K., (2003). Structural architecture of the ocean-continent boundary at an oblique transform margin through deep-imaging seismic interpretation and gravity modelling : Equatorial Guinea, West Africa. *Tectonophysics*, **374** : 19-40.

Whitmarsh, R. B. & Miles, P. R., (1995). Models of the development of West Iberia rifted continental margin at 40 degrees 30'N deduced from surface and deep-tow magnetic anomalies. *Journal of Geophysical Research*, **100**, 3 : 3789-3806.