Geophys. J. Int. (2005) **162,** 793–810 doi: 10.1111/j.1365-246X.2005.02668.x

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

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Accepted 2005 April 25. Received 2004 October 14; in original form 2004 May 13

SUMMARY

Deep penetration multichannel reflection and Ocean Bottom Seismometer wide-angle seismic data from the Congo–Angola 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 30–40 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 prevailed—compared to horizontal motions—during the formation of the basin.

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

1 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 –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, OBS) 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.

2 GEOLOGICAL SETTING

The South Atlantic Ocean, between Africa and South America, is divided into four segments (Fig. 1): (i) the equatorial segment, between about 10°N and the Equatorial Fracture Zones system (Saint-Paul,

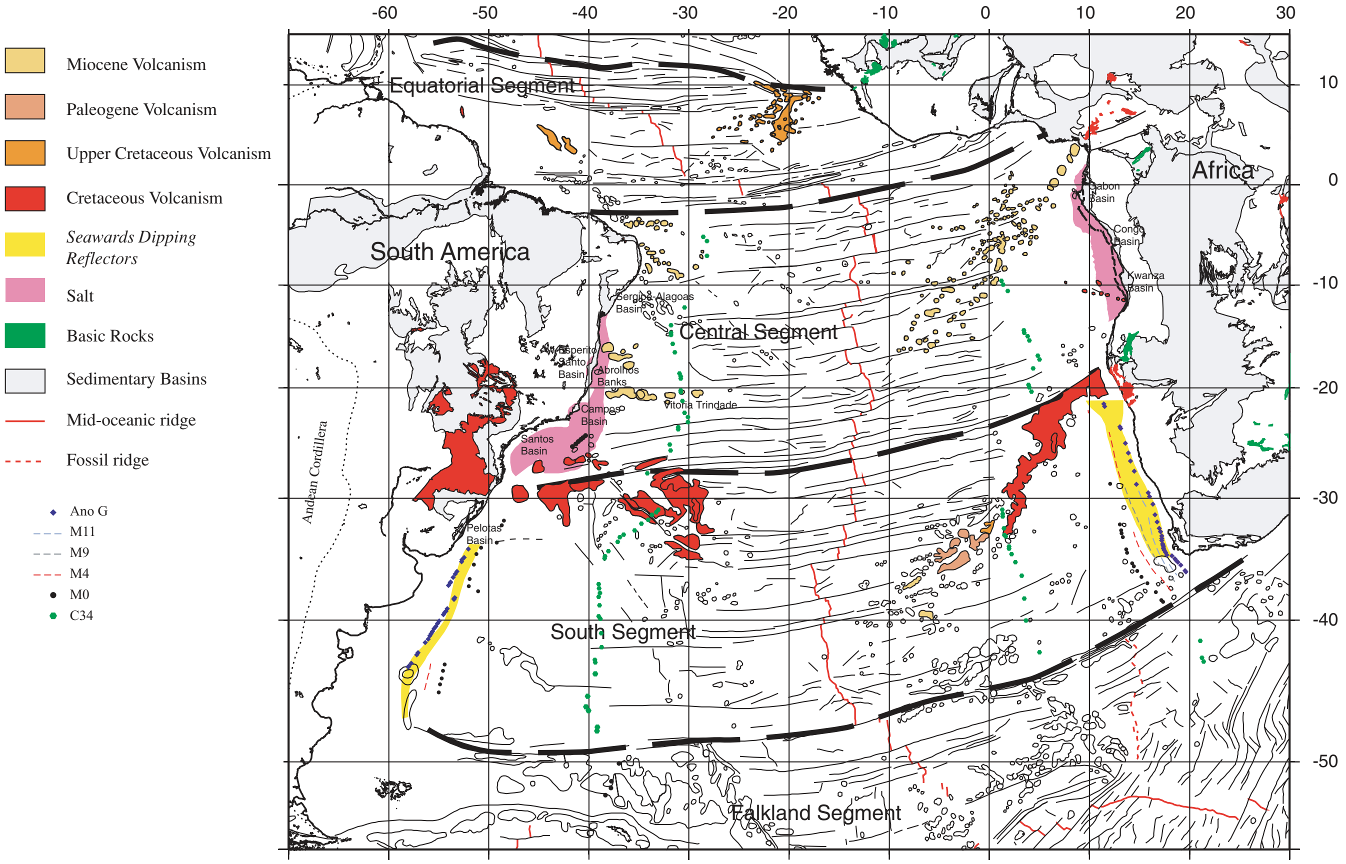

Figure 1. General structural map of the South Atlantic Ocean. Boundaries between the four segments are in broken black lines. Fracture zones and seamounts are based on interpretation of the gravity map (Sandwell and Smith satellite derived gravity data, grid 1 × 1 min, personal communication). The salt boundary is in pink (after Pautot *et al.* 1973; Renard & Mascle 1974; Emery *et al.* 1975; Leyden 1976; Mascle & Renard 1976; 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 (symbol or thin colour 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 Cande *et al.* (1988).

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.

The South Atlantic Ocean started opening 140 Ma (Lower Cretaceous), during the western Gondwana breakup. 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–M11, Rabinowitz & LaBrecque 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 (144.2–124 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 (Teisserenc & Villemin 1990; Vernet *et al.* 1996); (iii) a later episode, characterized by a lacustrine sedimentation deposited during Barremian to Middle Aptian times (127–117 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 (Teisserenc & 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 silicoclastic 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; Walgenwitz *et al.* 1990; Lunde *et al.* 1992; Walgenwitz *et al.* 1992 in Anka & Séranne 2004; Burke 1996).

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 1 km 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, 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 *et al.* 1989; Duval *et al.* 1992; Davison 1999), then the pre-salt sediment infill is also pre-breakup and the substratum is continental or subcontinental (for instance, thinned continental crust intruded by mantle material immediately prior to seafloor 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 *et al.* 1998; Marton *et al.* 2000), then it is possible that the salt was partly deposited on a non-continental substratum (as suggested by Jackson *et al.* 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 (2000 m) and that Loeme equivalent evaporites cannot exist in the outer basin. The observed outer diapiric structures could be (1) pre-Loeme syn-rift evaporites (5–10 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.

3 STUDY AREA AND DATA

The study area is located in the central segment, off the West African margin, between Congo, Zaire and Angola (Fig. 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 200-m water depth contour line and at the west by the presumed oceanic crust boundary, is about 320 km wide, covering an area of 22 000 km^2. The main target, the Lower Congo basin, is about 250 km wide and located between Gabon and Angola, between the Mayumba apron and the Ambrizete Arch.

3.1 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 (5 km × 5 km) exist for the conjugated continental platforms, but these data, like the 3-D 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 Figs 1 and 2.

Single-channel seismic lines collected by academic institutions (Ifremer, 1971; Lamont-Doherty, 1966–1979; University of Texas, 1979; Woods Hole, 1972) in the late 1960s and early 1970s for regional reconnaissance. On the African margin, profiles are generally perpendicular to the margin, spaced every 100–200 km. 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.

2-D multichannel seismic (MCS) lines. On the African margin, long, regional MCS lines were collected off Gabon in 1989 during the (Proto Rift Ocean Basin Evolution) PROBE Programme; pre-salt, intracrustal and Moho reflections are clearly visible at depths of 10 s (two-way traveltime: 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 subsalt 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 1970s do not actually provide fully reliable information on the deep structure of the conjugated margins. On the African margin, Expanded Spread Profiles (ESPs) were shot in the mid-1980s to sample the deep structure of the South Gabon basin (Wanesson 1991); OBS data were also collected in the late 1990s, 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.*

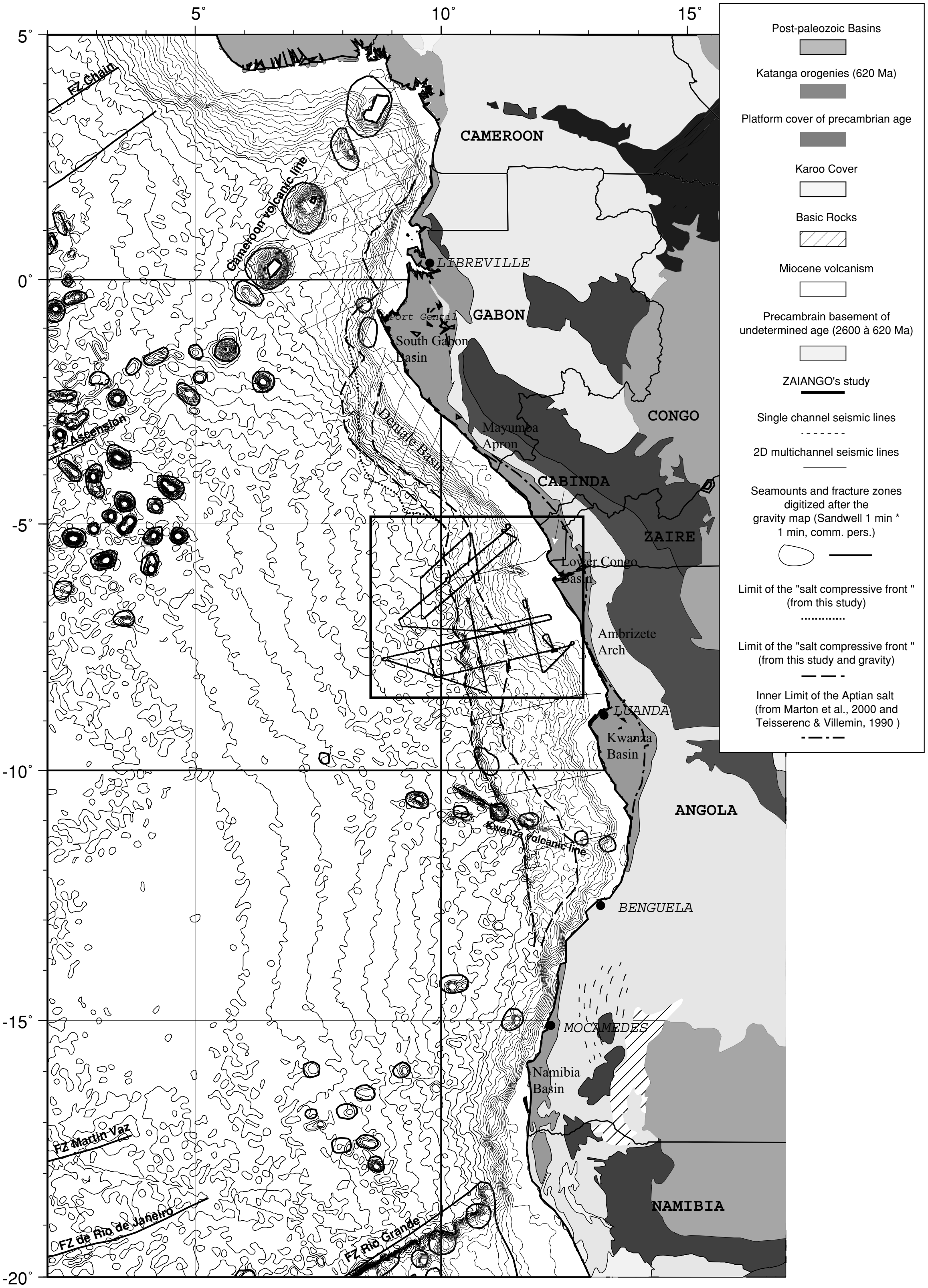

Figure 2. General predicted bathymetry map (after Sandwell & Smith 1997) of the West African margin between the equatorial fracture zones (to the North) and the Walvis Ridge (to the South). Fracture zones and seamounts are based on interpretation of the gravity map (Sandwell and Smith satellite derived gravity data, grid 1 × 1 min). Onshore geological structures are based on the digitization 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, ZaïAngo), Woods Hole, the University of Miami (PROBE) 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).

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 Fig. 3:

(i) A set of six 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.

(ii) MCS reflection data and OBS refraction data collected in March 2000 during the ZaïAngo programme (Savoye, unpublished internal report, 1999), a joint project conducted in the years 1998–2001 by Ifremer and Elf. Seventeen profiles were shot during the ZaïAngo cruise, for a total of 3180 km 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:

(i) Profile 3 is 320 km long (with nine OBSs, evenly distributed every 25 km over a 200-km-long section) and partly implemented along industrial lines A84-74 and GWA88-1075.

(ii) Profiles 7 and 11 were merged into one single line, named '7 + 11' hereafter. This line is 400 km long (with 26 OBSs, unevenly distributed every 7.5 or 15 km approximately over a 320-km-long section) and partly implemented along line A84-74.

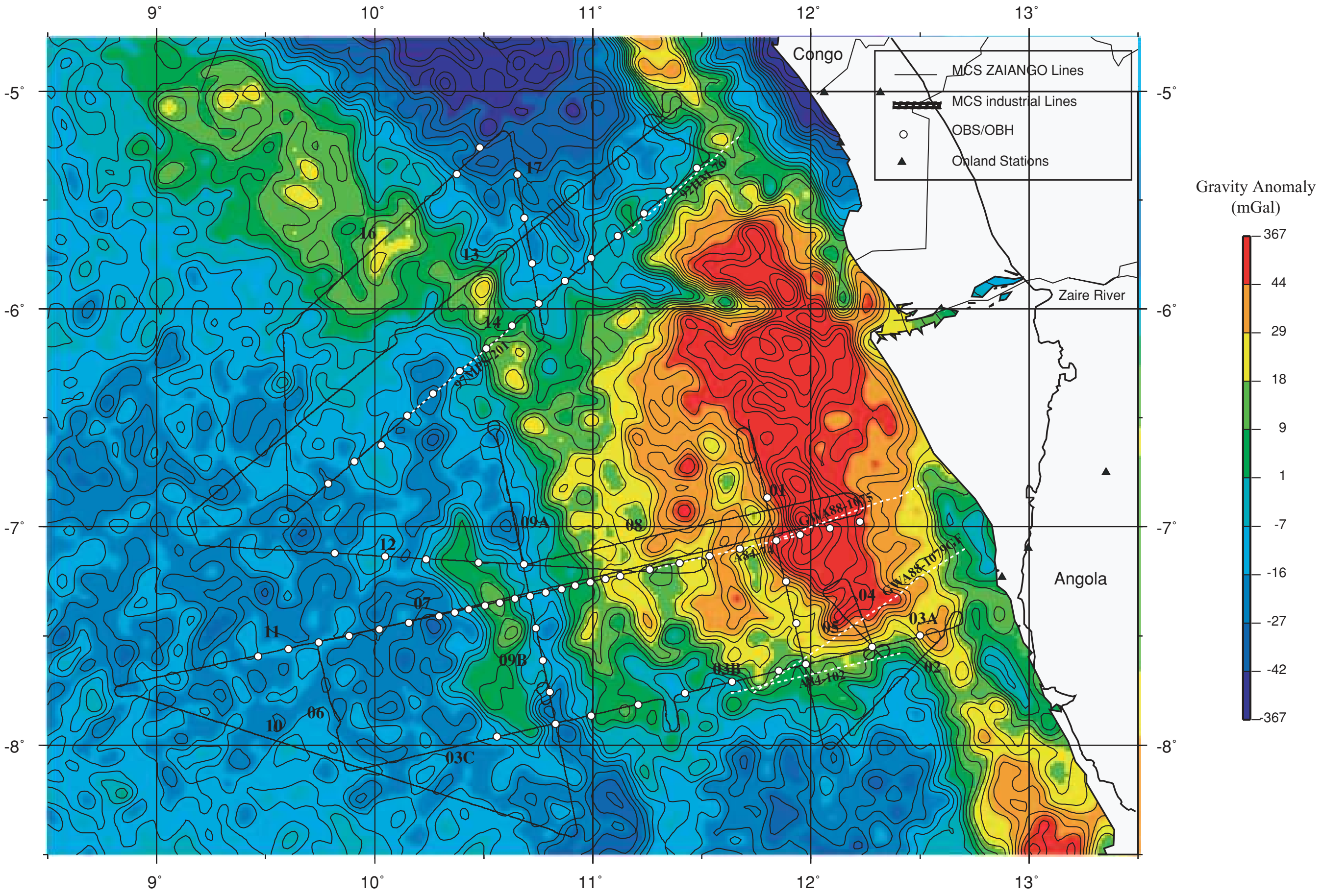

Figure 3. Gravimetric map (Sandwell and Smith satellite derived gravity data, grid 1 × 1 min) of the survey area and location of the seismic profiles, including the ZaïAngo lines (black lines, numbered from 1 to 17) and the industrial lines from Total used in the present study (in white tick: A84-102,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

(iii) Profile 12 is 210 km long; with five OBSs, evenly distributed every 20 km over a 80-km-long section.

(iv) Profile 14 is 270 km long (with 14 OBSs, evenly distributed every 20 km; oriented NE-SW; crossing the Zaire canyon) and partly implemented along lines 97MPS-201 and 92HM-76.

(v) Profile 1 is perpendicular to lines 3 and '7 + 11'; 180 km long, with five OBSs evenly distributed every 25 km in its central part.

(vi) Profile 9 is perpendicular to lines 3, '7 + 11' and 12; 180 km long, with six OBSs evenly distributed every 25 km in its central part.

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

In addition: (i) one 100-km-long line (profile 2), implemented 35 km to the south of line GWA88-1079GF, was recorded on three 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 data set 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.

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 8–12 s (twt) below sea level—15–35 km in depth—by simultaneously recording MCS reflection data on a 4.5-km-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 m^3/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 in^3 array of 12 airguns (8×550 in^3, 2×75 in^3 and 2×150 in^3), towed 24–27 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 in^3 array of nine airguns (three, 550 in^3, 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 maximizes 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 in^3 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 airgun 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 bandpass 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; 7000–15 000 ms: 3 – 5 – 15 – 20 Hz); dynamic equalization; Kirchoff migration using a constant velocity of 1500 m s^{-1}; 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.

The seismic data generated by the non-conventional 'single-bubble' airgun array (Avedik *et al.* 1993) provide an image of deep structures located below the Aptian salt layer which were left unrevealed so far using conventional MCS techniques (Fig. 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 four zones, as shown in Fig. 5 (seismic sections) and in Fig. 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, unpublished internal report, 1999), zone I consists of unthinned, 30- to 40-km-thick continental crust.

Zone II (the continental slope domain) is about 50 km wide (Fig. 6). It is mainly covered by industrial seismic lines and by ZaïAngo lines 2 and 3. It can be subdivided into three subzones (IIa, IIb and IIc), characterized by different basement slope dip angles: 11°, 22° and 11°, respectively (Figs 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 (Fig. 7):

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

(ii) Only one or two tilted blocks are visible.

(iii) 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 10 km, and a maximum offset ranging between 2 and 4 km, assuming sediment seismic velocities of 5.5 km s^{-1}. 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

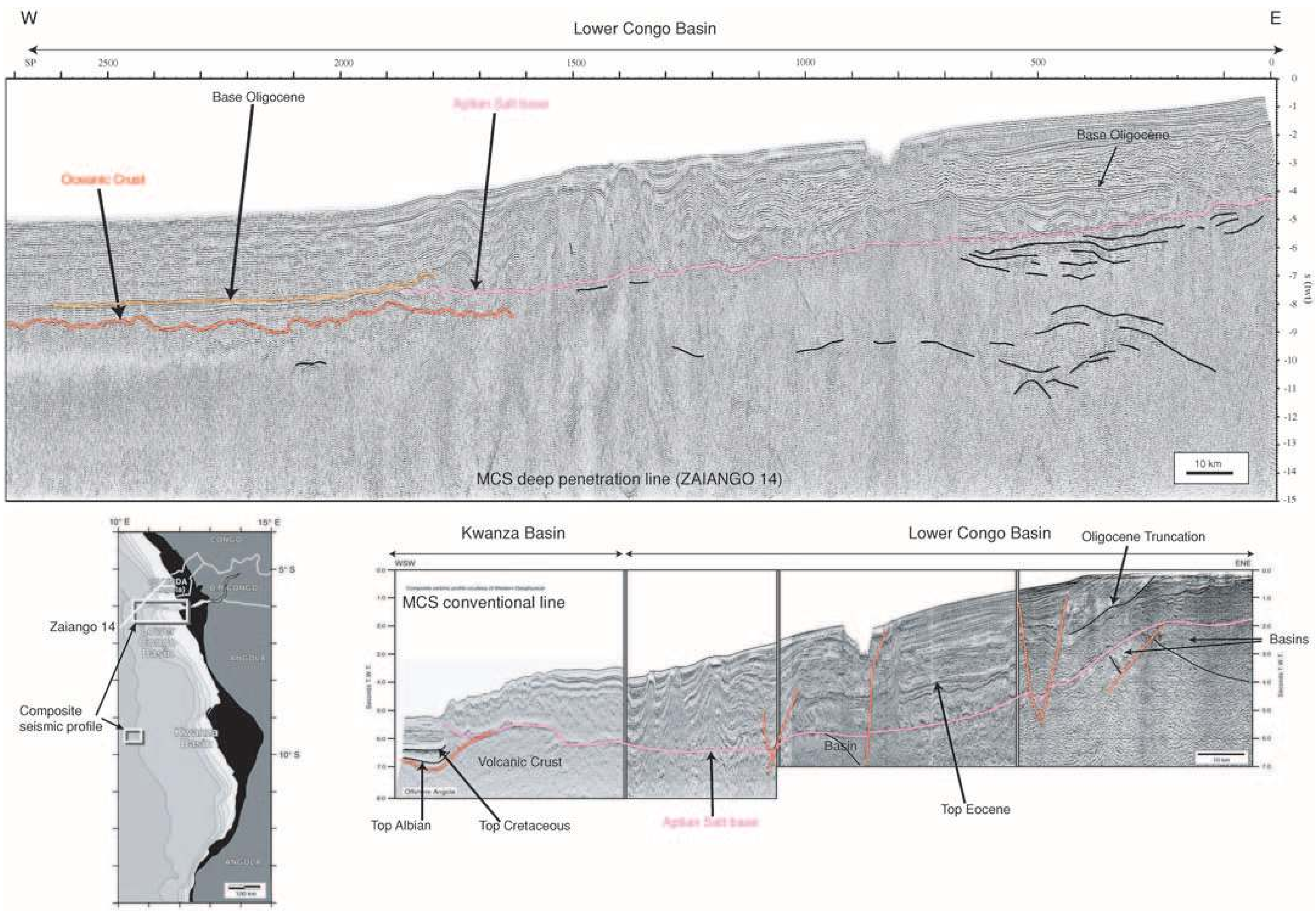

Figure 4. Comparison between ZaïAngo line 14 and one composite profile based on conventional seismic data acquired by Western Geophysical near the study area, across the Zaire Canyon (after Cramez & Jackson 2000). The ZaïAngo profile is migrated using a constant velocity of 1500 m s^{-1}. Note the difference in resolution for the post-salt series and the information provided by the ZaïAngo data beneath the salt screen.

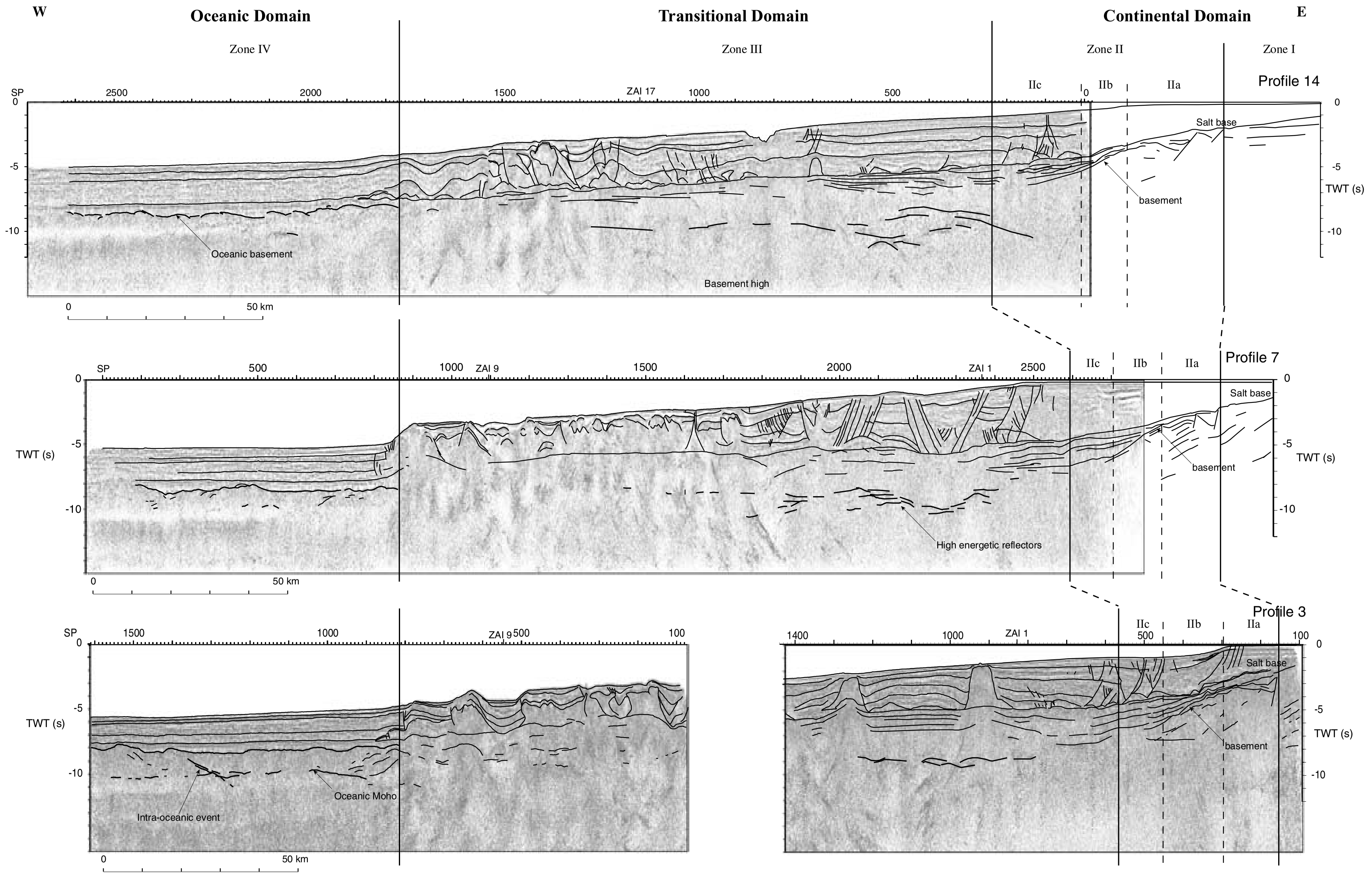

Figure 5. The three major seismic ZaïAngo transects (14, ‘7 + 11’ and 3, respectively) shot across the margin. Line drawings in the post-salt sediment layers and near the coast are based on the interpretation of the industrial lines (courtesy of Total). The salt base and the basement are underlined by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

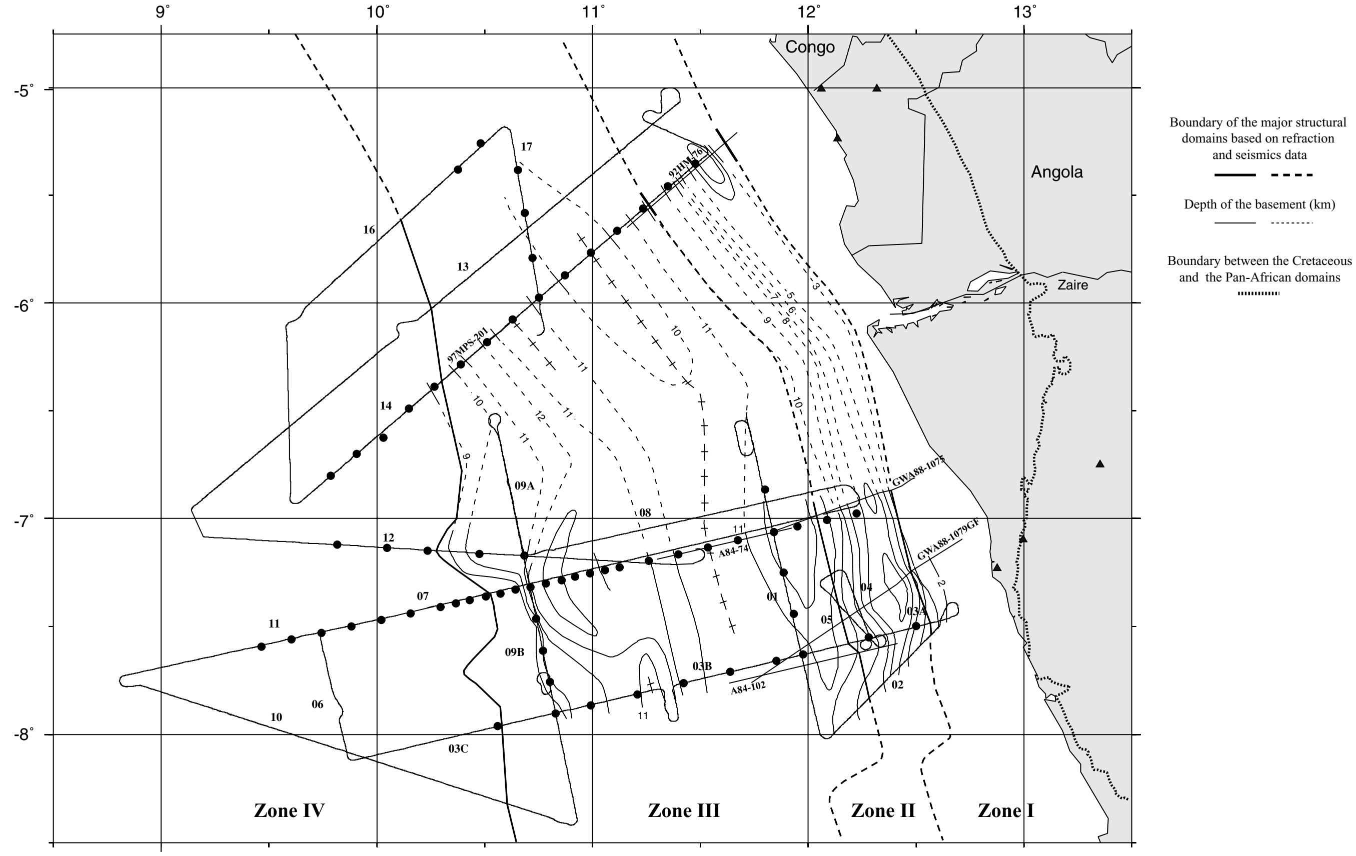

Figure 6. Structure contours on basement in the Lower Congo Basin, based on the OBS data of the ZaïAngo profiles (Contrucci *et al*. 2004). Contours are at 1-km intervals (sea level datum). Black thick lines delineate the major structural domains based on seismic and gravity data: zone I is the unthinned 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 ZaïAngo 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.

on the stratigraphic scale, the age of this discordance ranges between 115 (Haq *et al.* 1987; Odin & Odin 1990) and 128 Ma (Harland *et al.* 1990).

(iv) 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) −5 km—at the slope foot, to 0.1 s (twt)—about 500 m—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 Fig. 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 (144.2–112.2 Ma) times, were, if any, relatively limited.

Zone III is sampled by most ZaïAngo seismic lines (Figs 5 and 8). Its length, between the foot of the continental slope to the presumed oceanic crust boundary, is between about 160 (on ZaïAngo profile 14) and 180 km (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, 1–2 s (twt)—2–4 km—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)—3–10 km—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)—15–25 km 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 (Figs 7–9).

(i) The layering is flat, parallel to the base of the salt, over distances greater than 100 km (between shot points 500 and 1400 on profile 3).

(ii) 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, Fig. 9) could actually well be related to sedimentary processes (shale mass or diapirs) as inferred by Teisserenc & Villemin (1990, see Fig. 32) on the Gabon Margin.

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

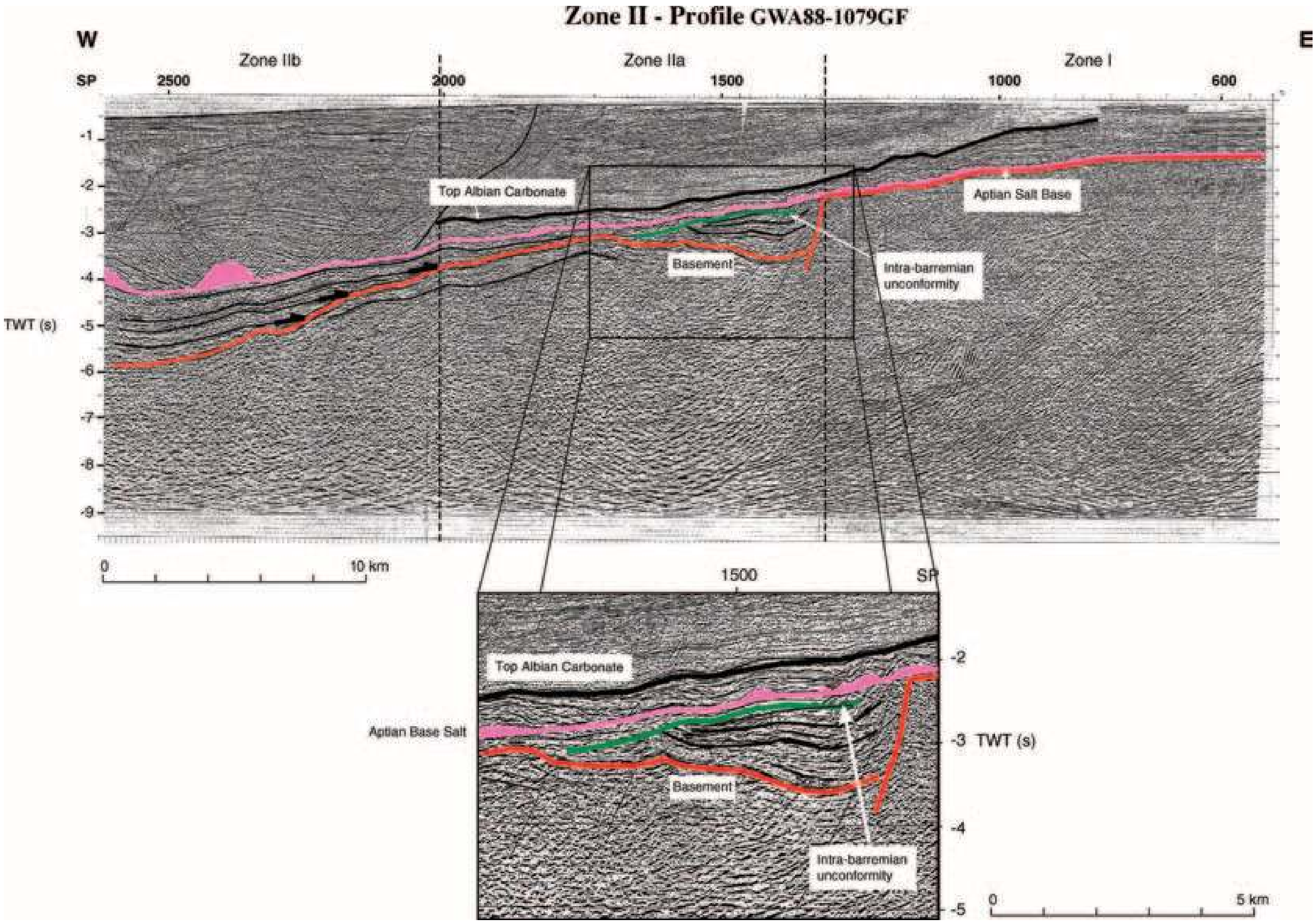

Figure 7. Industrial seismic line GWA88-1079GF (courtesy of WesternGeco) located in the continuation of ZaïAngo profile 3, below the continental shelf (Zones I, II). Thin line drawings are based on Total's preliminary interpretation; re-interpreted line drawings (this study) are indicated by bold lines: 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 characterized 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.

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 (Séranne *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)—7 km—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 (Fig. 5: shotpoint 1300). This event is comparable to those documented on the Iberia Margin (Pickup *et al.* 1996).

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 (Fig. 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 20 km, 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 (Fig. 5). It is also difficult to see any acoustic facies below this subzone.

7 REFRACTION DATA

OBSs and landstations 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 (Fig. 11):

(i) In Zones I–III, the post-salt sediment layers are characterized by seismic velocities (based on the OBS refraction data) lower than 5 km s^{-1}, except for the Albian (112.2–98.9 Ma according to the

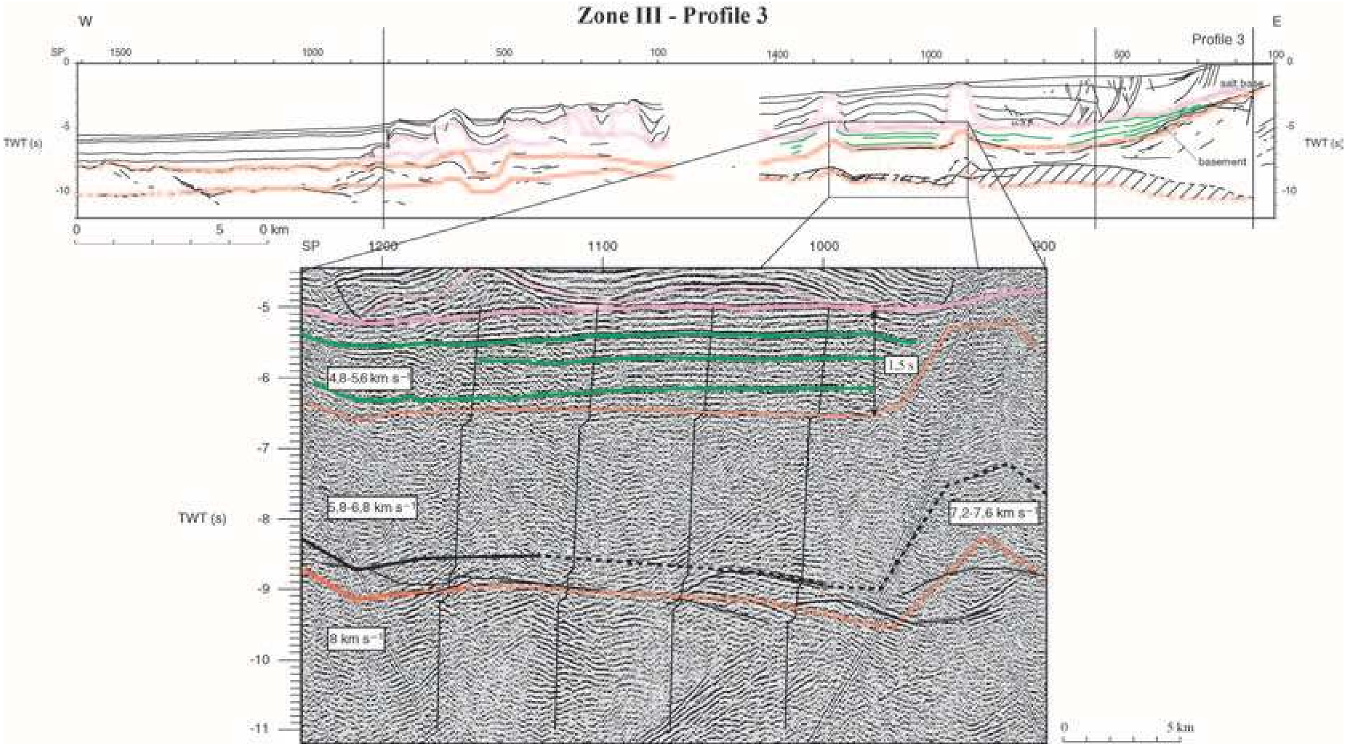

Figure 8. Zoom showing details for ZaïAngo profile 3. The localization of this zoom is shown on the line drawing about. Salt is in pink, the pre-salt sediment in green and the post-salt sediments and basement in the slope in black. The velocity model is superimposed in red for the basement and the Moho 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.

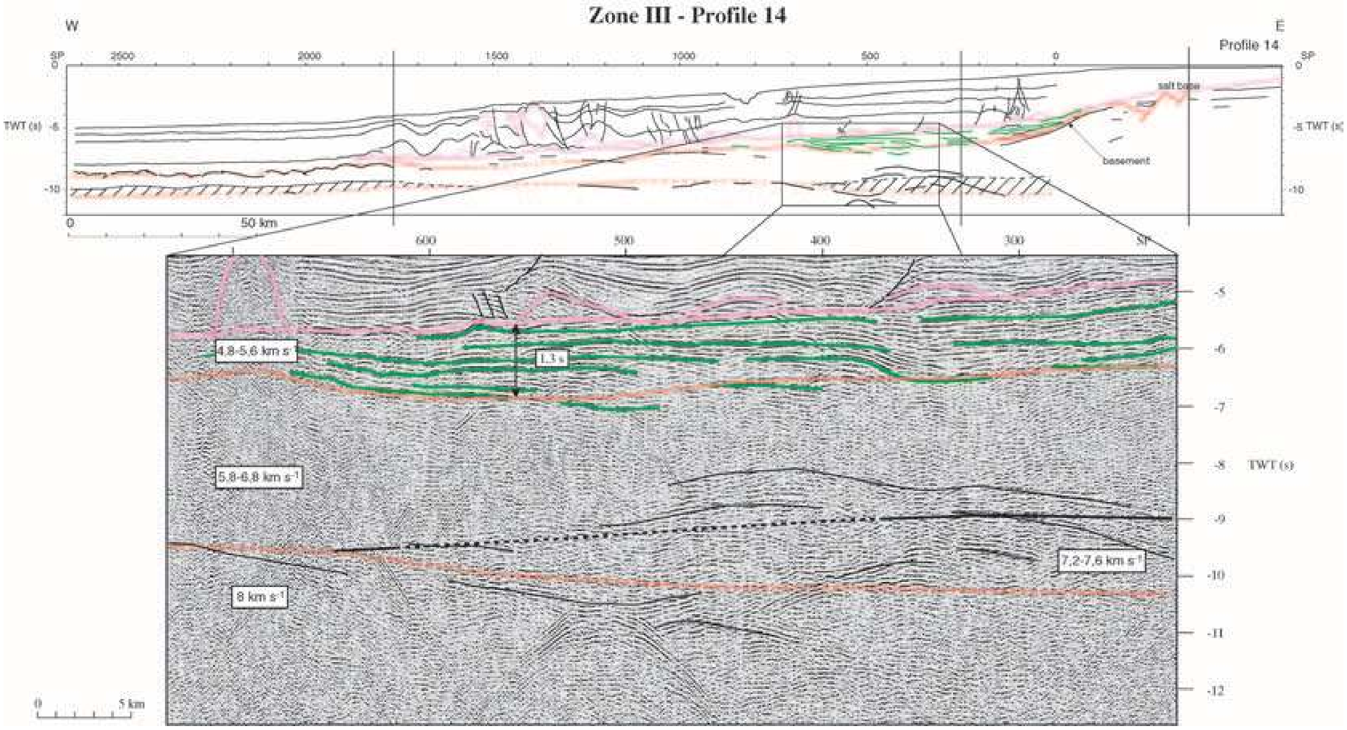

Figure 9. Zoom showing details for ZaïAngo profile 14. The localization of this zoom is shown on the line drawing about. Salt is in pink, the pre-salt sediment in green and the post-salt sediments and basement in the slope in black. The velocity model is superimposed in red for the basement and the Moho 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. SP = shot point.

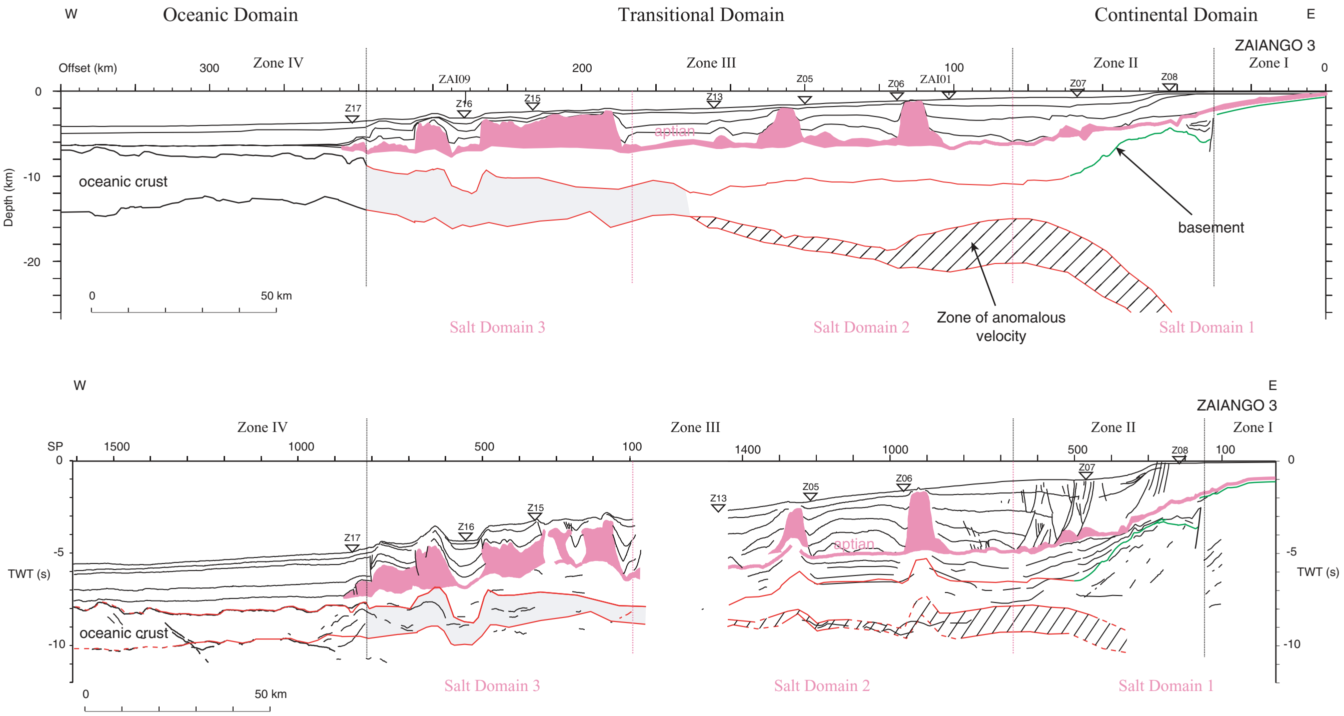

Figure 10. ZaïAngo profile 3 (in s twt) and the transformation in depth. The red lines indicate the velocity model (basement, anomalous velocity layer and Moho) based on the interpretation of the OBS data (Contrucci *et al.* 2004). The green line indicates the basement documented on the interpretation 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.

Cenozoic time table of Berggren *et al*. 1995) carbonates and salt layers, the velocities of which are above 5 km s^{-1}.

(ii) 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^{-1}. 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 4 km. 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).

(iii) 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 (at the top) and 6.8 km s^{-1} (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 50 km, from 30–40 km (based on gravity data and also on landstations data, Matias (personal communication, 2002)) below the continental platform to less than 5 km (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 6 (on profile 3) to 10 km (on profiles 7–11) below the post-salt sediment depot-center to a thickness of 3–4 km 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 (6.6–6.8 km s^{-1}). On profiles 3 and 12, the basement high is not documented, but this may be due to the OBS distribution.

(iv) Below this crustal layer, anomalous velocity layers (7.2–7.8 km s^{-1}—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 4–6 km thick, with velocities ranging between 7.2 and 7.6 km s^{-1}, 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 2 km thick, with velocities between 7.4 and 7.8 km s^{-1}, is also present at the boundary between the transitional and oceanic domains (on profiles 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 and 7.4–7.8 km s^{-1}), 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 subbasins, 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 (Fig. 11): 'Type I' crust is found in the eastern part of the basin. It is characterized by an upper layer of thickness greater than 5 km (average thickness is 5.5 km on profile 3; about 8 km on profile '7 + 11'; 8.5 km on profile 14), lying over an anomalous velocity layer (7.2–7.6 km s^{-1}), up to 6 km 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 5 km) decreases from east to west. Clearly, there is no anomalous velocity layer at its base, except

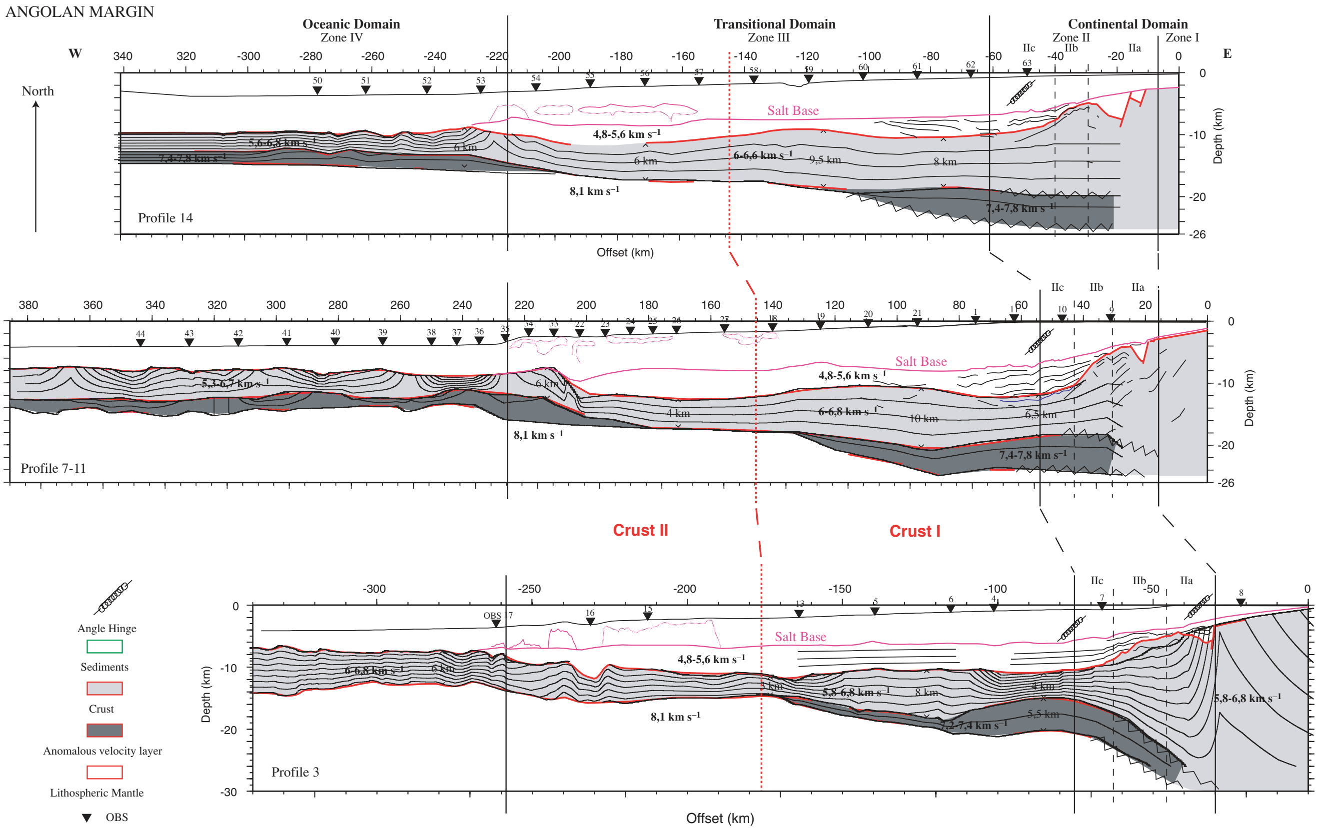

Figure 11. Synthesis of main results, based on refraction, MCS and gravity data. Black and green lines are based on the interpretation of ZaïAngo data; blue lines, on the interpretation of the industrial lines; red lines indicate the velocity interfaces, based on the interpretation of the OBS data, delineating 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 Zones I–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, isovelocity curves) are indicated.

near its western termination, where a basement ridge and a thin, (2 km), high-velocity layer (7.4–7.8 km s^{-1}) 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:

(i) 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 (Austin & Uchupi 1982; Bauer *et al.* 2000). 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 (Fig. 12): on the Greenland margin (Korenaga *et al.* 2000), for instance, the 4-km-thick SDRs layer lies on top of a 30-km-thick igneous crust and extends over a lateral distance of 150 km; in contrast, the SDR layers on the Sergipe–Alagoas margin extends over less than 20 km and its maximum thickness is less than 1 s (twt)—about less than 3 km (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.

(ii) Crustal thinning is very abrupt and occurs mostly below the continental slope: crustal thickness decreases from more than 30 to about 5 km (on profile 3), over a lateral distance of less than 50 km (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

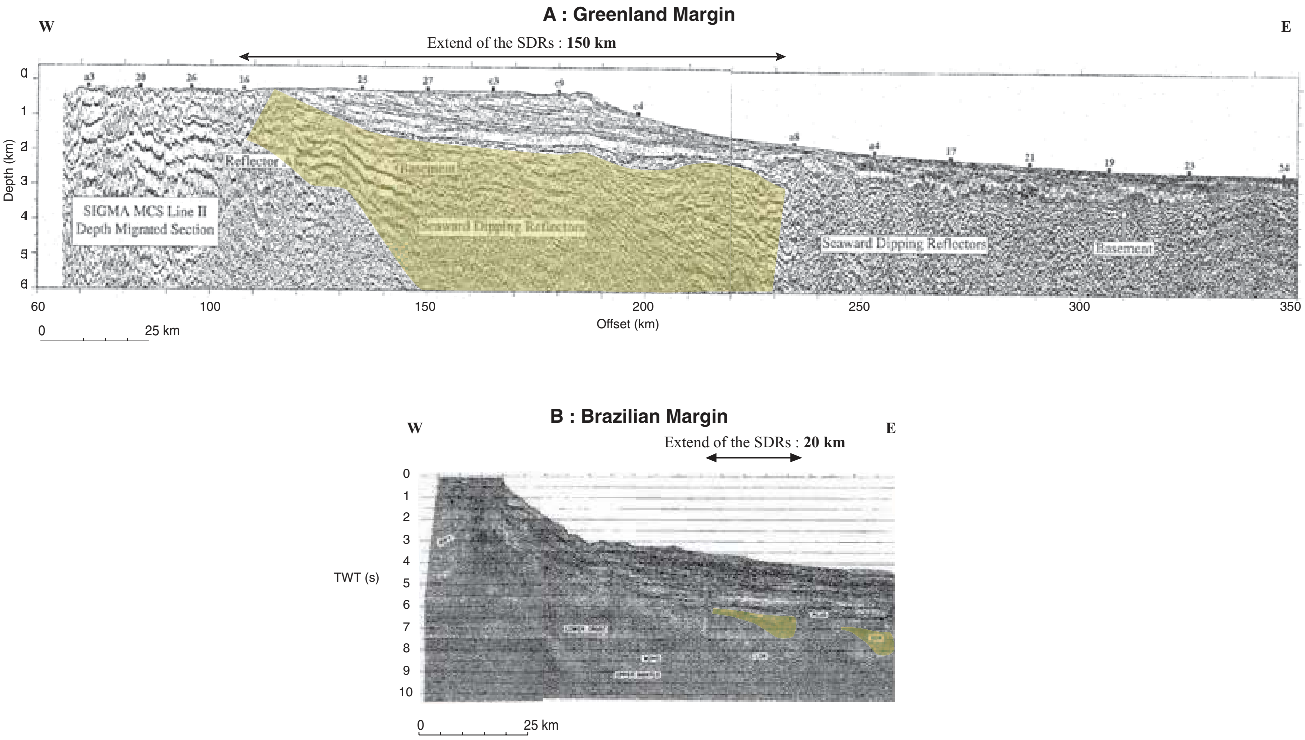

Figure 12. Comparison between two continental margins (Brazilian Margin and Greenland volcanic margin). Low energy reflectors interpreted as SDRs on the Brazilian profile (Mohriak *et al.* 1995) and the 4-km-thick SDR layer on the Greenland profile (Korenaga *et al*. 2000) are underlined in yellow. Note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

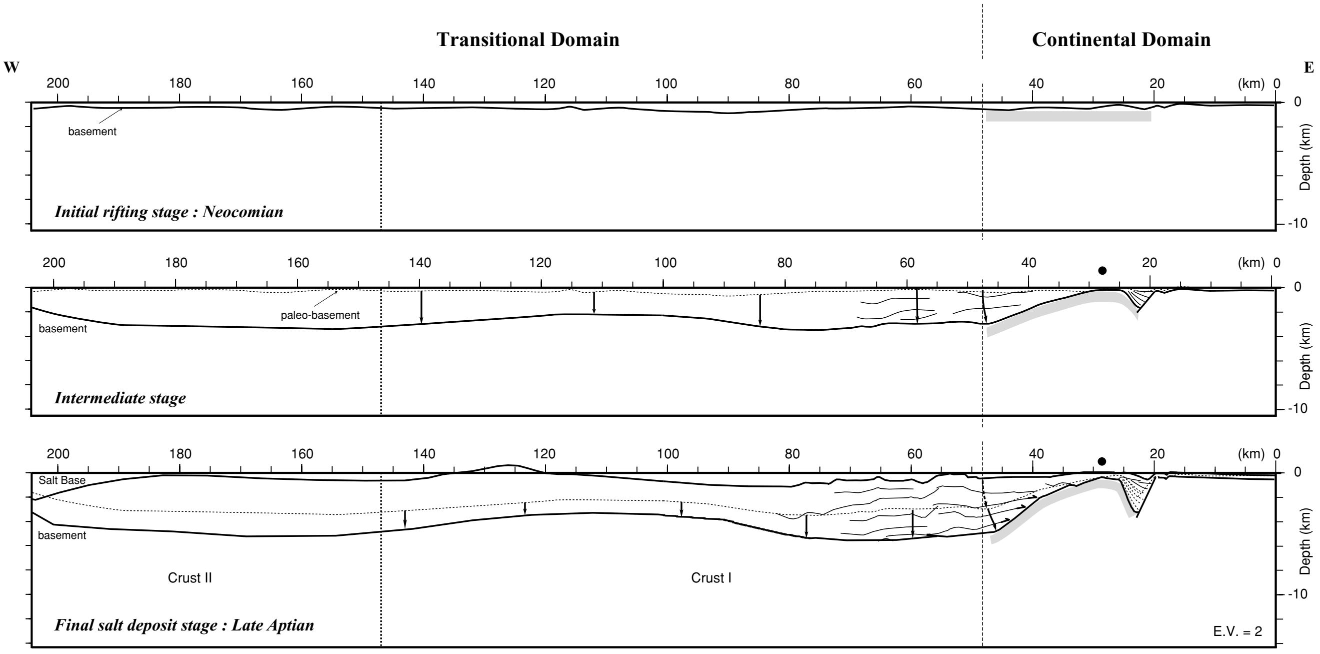

Figure 13. Pre-breakup tectonic evolution of the Angolan margin on the basis of profile ZaïAngo 7, from Neocomian (144.2 Ma) to Late Aptien (112.2 Ma). The black line corresponds to the basement; dotted lines represent the paleobasement of the precedent stage. The motion in the continental domain may be assimilated to a rotation (grey zone and curved arrows; the black dot indicates approximately the centre 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).

salt deposition. If present, tilted blocks at the slope foot or in the deepest part of the basin are necessarily of limited size, that is, too small to be visible on the MCS sections. No imprint of significant extension is observed to explain this crustal abrupt thinning.

(iii) The Angolan Margin is characterized by the existence of a 200-km-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 subsalt 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.

(iv) 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 (Fig. 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.

(v) 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.

(vi) 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 (Fig. 13). The about-zero level salt layer deposition constrains the palaeogeometry 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.* 2005). 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 & 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 ZaïAngo, the compilation of a published profile (Mohriak *et al.* 1990) and an industrial profile (Total), exhibits an slightly smaller, analogous structuration than the ZaïAngo 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.

ACKNOWLEDGMENTS

The ZaïAngo research programme was financially and technically supported by Ifremer and Total. We acknowledge B. Savoye (Ifremer) and A. Morash (Total), the project coordinators, who made possible the present seismic experiment. We thank Total for the financial and scientific support of this project, especially P. De Clarens, P. Bourges and H. Pigeyre. We thanks also Sonangol for their participation of the ZaïAngo research programme. We thank WesternGeco for allowing the publication of the seismic line in Fig. 7. The GMT software (Wessel & Smith 1995) package was used in the preparation of this paper. We would like to thank the reviewers Prof. P. Huchon and E. Flueh and the editor Dr G. Laske, who helped to improve significantly the version of the manuscript. We thank the crew of both R/V Le Nadir and R/V Le Suroit. We also thank Walter Roest and Marina Rabineau for their language corrections.

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