APÊNDICE B - Crustal architecture of the Almada basin, NE Brazil: an example of a non-volcanic rift segment of the South Atlantic passive margin (Artigo Científico)

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Crustal architecture of the Almada Basin, NE Brazil: an example of a non-volcanic rift segment of the South Atlantic passive margin

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Abstract: The Almada Basin, located in the southern Bahia State segment of NE Brazil, shares a similar sedimentation history and stress regime with the other eastern Brazilian basins. But when considering the composition of the transitional crust, a remarkably different behaviour is observed between the Almada Basin and the other eastern Brazilian basins. The architectural elements of the basin such as the reflection Moho discontinuity, the oceanic and continental basements, and the sedimentary section, as well as the tectonic style, are discussed in this study using gravity, seismic, regional geology and well-drilling results.

The Almada Basin is part of a continental rift system that developed during the Early Cretaceous, heralding the Gondwana break-up and subsequently evolving into a passive divergent margin. Deep seismic profiles show the progressive thinning of the continental crust but there is no clear evidence of mantle exhumation.

The Almada Basin is the conjugate margin of the South Gabon Basin in West Africa. Although both basins display similar stratigraphic record and geological evolution, the rifting mechanism resulted in a considerable asymmetric break-up. The Almada Basin is floored by the Itabunas–Salvador–Curaçá Belt of the São Francisco Craton and is characterized by Palaeoproterozoic granulites in a high-angle east-dipping thrust fault regime. However, the South Gabon Basin lies on the Neoproterozoic West Congolian Belt that is made up of low- to medium-grade metamorphic rocks in a low-angle thrust tectonic regime. The Precambrian basement fabric of both the Almada and South Gabon basins is marked by lithospheric-scale discontinuities that controlled the implantation of the rift zone and the extension style during the Mesozoic. The strong basement structural inheritance can be recognized in both the geological and geophysical records.

The key architectural elements of a volcanic margin, such as large igneous provinces, seaward-dipping reflectors and the basinal syn-rift magmatism, are not recognized in the Almada Basin. Although the South Atlantic margin is mostly volcanic in the southernmost segment, the presence of these two non-volcanic segments – the southern Bahia State and the southern Gabon – are important as a record of the differences in the geotectonic process that governed the formation of the South Atlantic divergent margins.

The South Atlantic divergent margin (SAM), which extends from the southernmost Austral Basin in south Argentina up to the Pernambuco Basin in NE Brazil, is highly complex and varied along the approximately 7500 km of coastline (Fig. 1a). The Almada Basin and the neighbouring basins of Camamu (to the north) and Jequitinhonha (to the south) are all located in the State of Bahia, and are known as the 'southern Bahia State basins'. These basins share similar characteristics with other eastern Brazilian basins when analysed in terms of major sedimentation history and dominant stress regime during the rift phase (Asmus 1984; Mohriak 2003). However, there is a noticeable absence of syn-rift magmatic activity that differentiates this segment from the other Brazilian segments, as is observed in the seismic profiles as well as in the results of 205 wells drilled to date (Asmus & Porto 1980; Chang *et al.* 1992).

In this article, we present the major architectural elements of the Almada Basin, such as the Mohorovičić discontinuity, the crystalline basement and the Precambrian inheritance, the oceanic basement, the sedimentary section, and the tectonic style that the basin exhibits using gravity, magnetic, seismic and well-drilling results. By using different data sets, we analyse: (1) the lack of volcanic elements; (2) the possible mechanisms that drove the evolution

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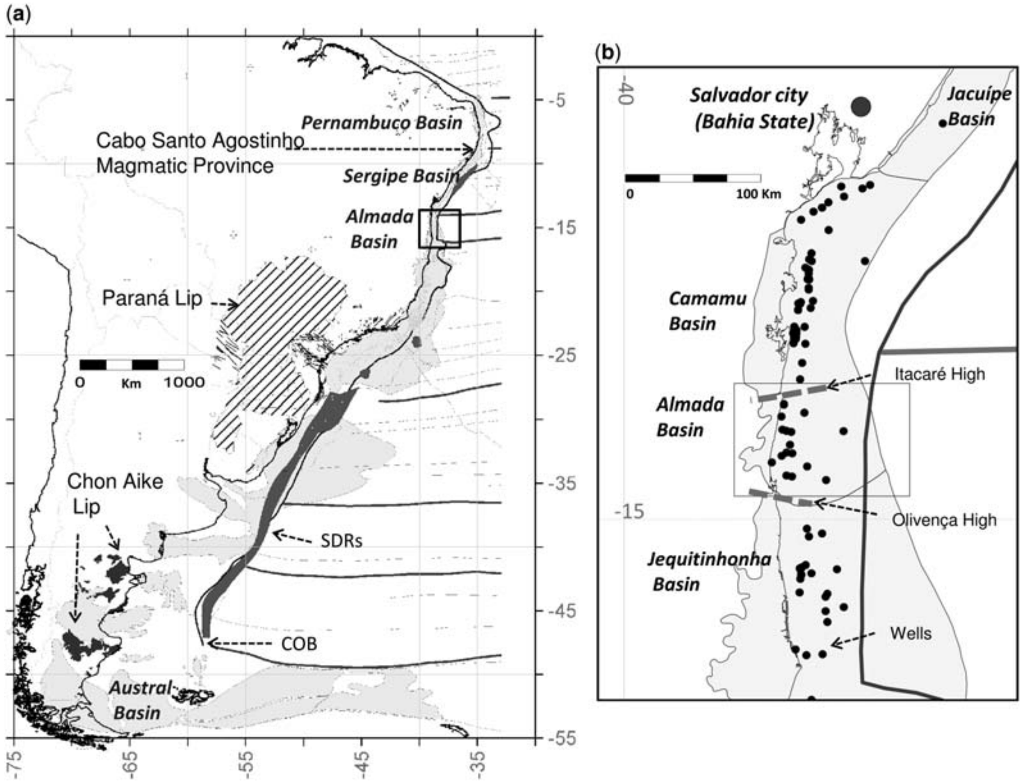

Fig. 1. (**a**) The South Atlantic divergent margin and the major syn-rift magmatic elements. (**b**) Location map of the southern of Bahia State basins and the area of study.

of the Almada Basin; (3) the difference in style that this segment exhibits in the context of the South Atlantic margin; and (4) a comparison with the South Gabon conjugate margin.

Data set and the regional geological framework

The Almada Basin has an extensive database that includes a three-dimensional (3D) seismic volume of 3400 km^2, more than 2000 km of 2D seismic lines, regional gravity–magnetic shipborne surveys and 28 wells drilled to date. The large 3D survey, acquired with a cable length of 6 km and 9.2 s of recording time, resulted in good seismic images of the rift deep structure. Four dip lines from the 3D and 2D seismic data sets (sections A–D) were chosen to illustrate the crustal behaviour of this basin. In addition, 2D gravity forward modelling was integrated with the seismic analysis to corroborate the geological model. The geological sections modelled by gravity data were constrained not only by the seismic interpretation and well-log densities offshore but also by the published maps and lithostratigraphic reports from the Brazilian Geological Survey (Companhia de Pesquisas de Recursos Minerais, CPRM) onshore.

The Almada Basin is a narrow basin, less than 120 km wide, located on Brazil's NE coast between approximately 14° and 15°S and 38° and 39°14′W. The basin is bounded to the west by a SW–NE trending normal fault system, and to the north and south by the basement highs of Itacaré and Olivença, respectively. The basement highs are the limits that separate the Almada Basin from the Camamu and Jequitinhonha basins (Fig. 1b). The Almada Basin developed over the São Francisco Craton, which consists of the lateral accretion of Precambrian high-grade metamorphic terrains (Alkmin 2004). In the tectonic–sedimentary evolution four main stages known as the pre-rift, rift, post-rift and drift stages are traditionally interpreted in the Brazilian geological literature (Chang *et al.* 1992; Mohriak 2003). The stratigraphic record of the basin is divided into four main units: (1) the pre-rift sequence; (2) the rift sequences; (3) the transitional sequence; and (4) the marine sequences, as

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can be observed in the comparative stratigraphic chart of Figure 2 (Logar 1983; Teisserenc & Villemin 1989; Gontijo *et al.* 2007).

The pre-rift sequence is comprised of fluvio, deltaic and aeolian continental sediments that were deposited in a continental syneclise during the Jurassic–Berriasian times, and exhibits a maximum thickness of the order of 500 m (Gontijo *et al.* 2007; Gordon 2011). The Sergi Formation, from this sequence, is well known as the most common hydrocarbon reservoir in the basin.

The rift sequences are mostly composed of fine-grained lacustrine deposits, and minor fluvio, fan delta and lake-turbidite sandstones. The lacustrine shales are considered the main source rocks in the region while the sandstones, drilled in several wells, are good reservoirs. In the rift section, three sequences from the Berriasian–Early Aptian times have been identified as accumulating approximately 3300 m of sediments deposited in a series of progressively younger sub-basins from onshore to deep water (Gontijo *et al.* 2007; Gordon 2011).

The post-rift (or transitional) stage consists of Late Aptian evaporites deposited from the platform to the continent–ocean boundary formed during the Gondwana break-up that heralded the opening of

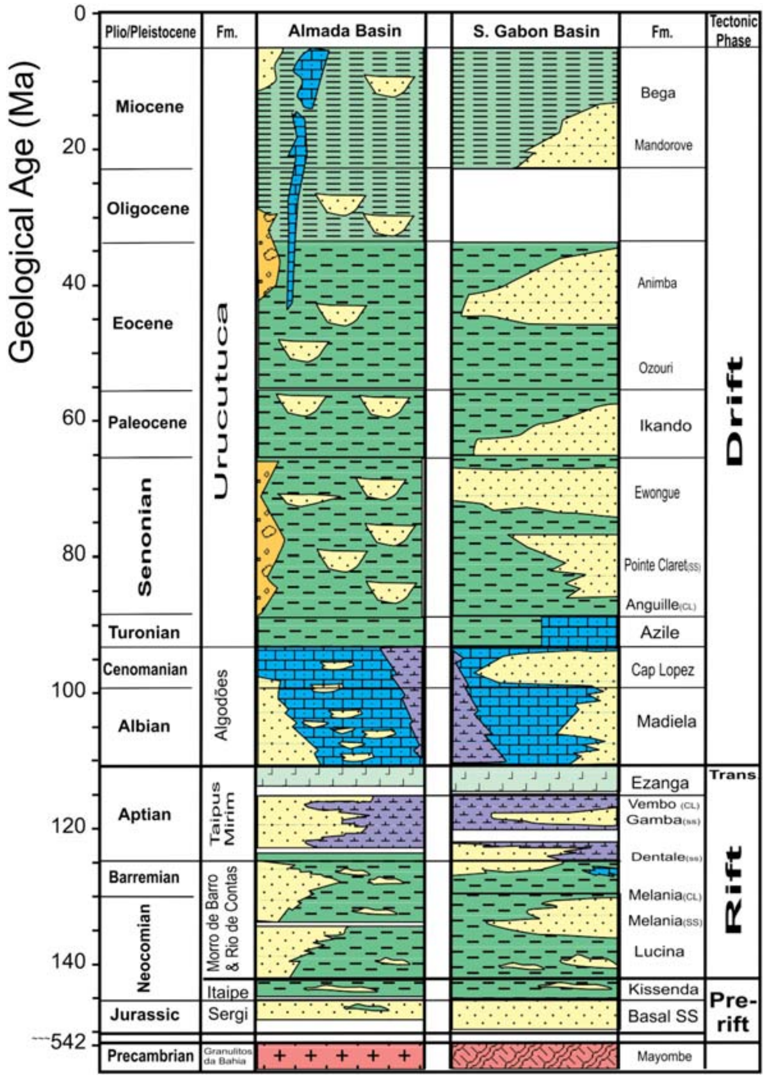

Fig. 2. Comparative stratigraphic columns of the Almada and South Gabon basins (after Logar 1983; Teisserenc & Villemin 1989; Gontijo *et al*., 2007).

the South Atlantic Ocean. The discrete salt deposits exhibit pillows and diapir structures that can reach a maximum height of approximately 2500 m, which are recognizable in the seismic record (Gordon 2011).

The basin evolved later into a marine passive divergent margin during the drift stage. The marine phase comprises three distinct sequences: (1) the Albian–Turonian carbonates deposited in a neritic environment in a shallow and narrow sea; (2) the transgressive marine system, from Cenomanian to Maastrichtian, characterized by siliciclastic and marls; and (3) the Tertiary regressive system, which comprises coarse-grained sandstones, platform carbonates and distal mudstone sedimentary beds (Chang *et al.* 1992). The drift sequences are greatly affected by gravitational tectonics such as halokinesis and shale diapirs, reaching a maximum thickness of the order of 1500 m (Gontijo *et al.* 2007; Menezes & Milhomem 2008; Gordon 2011).

The Almada Basin architectural elements

The Mohorovičić discontinuity (Moho)

In the São Francisco Craton, regional gravity data and seismological interpretations have been used to define the Moho depth (Motta *et al.* 1981). The maximum crustal thicknesses found by those authors were of the order of 40–43 km, in the central part of the craton, decreasing eastwards to approximately 32 km at the coastline. In the offshore Almada Basin, the good quality of the 3D seismic profiles reveal a distinctive band of strong layered reflectors (compatible with the base of the crust), as well as different reflectivity patterns. The low-reflectivity seismic facies have been interpreted as indicative of upper mantle and upper continental crust and oceanic basement. In contrast, the high-reflectivity facies appear to be characteristic of lower continental crust, as has been reported in several basins worldwide (Mohriak *et al.* 1990; Rosendahl *et al.* 1992, 2005), and we assumed that the seismic reflection Moho corresponds to the base of this package. The seismic examples of sections C and D (Figs 3 & 4), located in the southern part of the basin (Fig. 5), are presented in a seismic amplitude attribute display, tecva (Bulhões & Nogueira 2005) in order to enhance the visualization of the seismic textures and the fault patterns. The Moho discontinuity shows a gentle dip towards the continent. In the eastern part of section C, the Moho exhibits an offset probably caused by a major listric fault system (Fig. 3). Offset of the Moho discontinuity has been described several times in the geological literature (e.g. Mooney & Meissner 1992). In the Almada Basin, this feature is probably an indication of the structural state of the crust under extension. The 3D seismic interpretation of the top and the base (Moho) of the crystalline basement allows the mapping of the thickness of the crust in the Almada Basin and in the São Francisco Craton (Fig. 5). This map shows a progressive thinning of the crust from west to east.

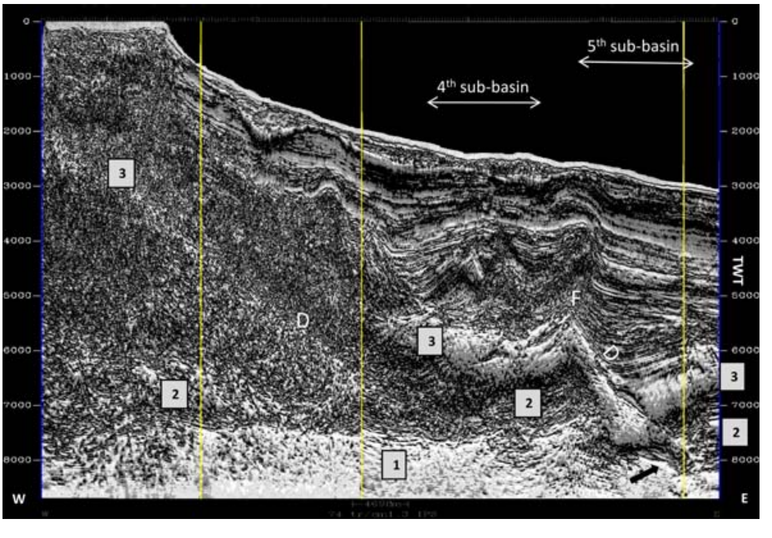

Fig. 3. Detailed seismic section C, located in Figure 5 and displayed in tecva attribute. Showing the following geological features: (1) interpreted as Moho; (2) the lower crust; (3) the upper crust; (D) the detachment faults and (F) thrust faults related to salt tectonics.Fourth and fifth are half-graben sub-basins. The black arrow signalizes the possible Moho offset below the fifth sub-basin. Reproduced courtesy of PGS do Brasil.

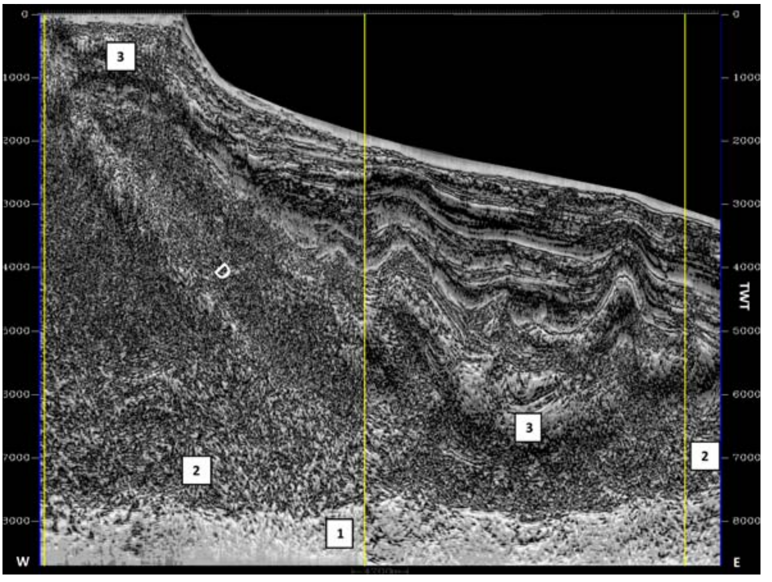

Fig. 4. Detailed seismic section D, located in Figure 5 and displayed in tecva attribute. Seismic facies references are the same as in Figure 3. Reproduced courtesy of PGS do Brasil.

Offshore, the lateral changes in thickness observed are reflecting the development of the sub-basins. The positioning of the Moho discontinuity, imaged in the seismic sections, is corroborated by the gravity interpretations shown in Figure 6. In this figure, we use interactive forward modelling (Talwani *et al.* 1959) derived from geological models (lower panels). These modelled gravity anomalies (solid lines in the upper panels) demonstrate a good fit to the observed gravity data (crosses in the upper panels) within experimental errors.

In the classical NVM, the transitional crust is highly stretched and, in some cases, even shows evidence of exhumed subcontinental mantle (e.g.

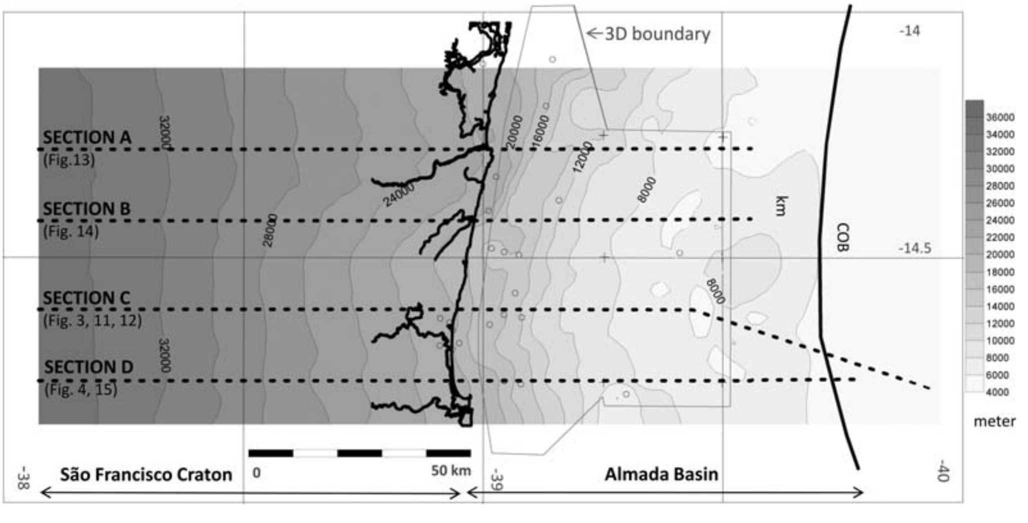

Fig. 5. Almada Basin and São Francisco Craton crustal thickness map (contours in metres). Dashed lines A–D indicate the location of the gravity profiles shown in Figure 6. Open circles represent the wells drilled in the area. COB is the crust–ocean boundary after Davison (1999).

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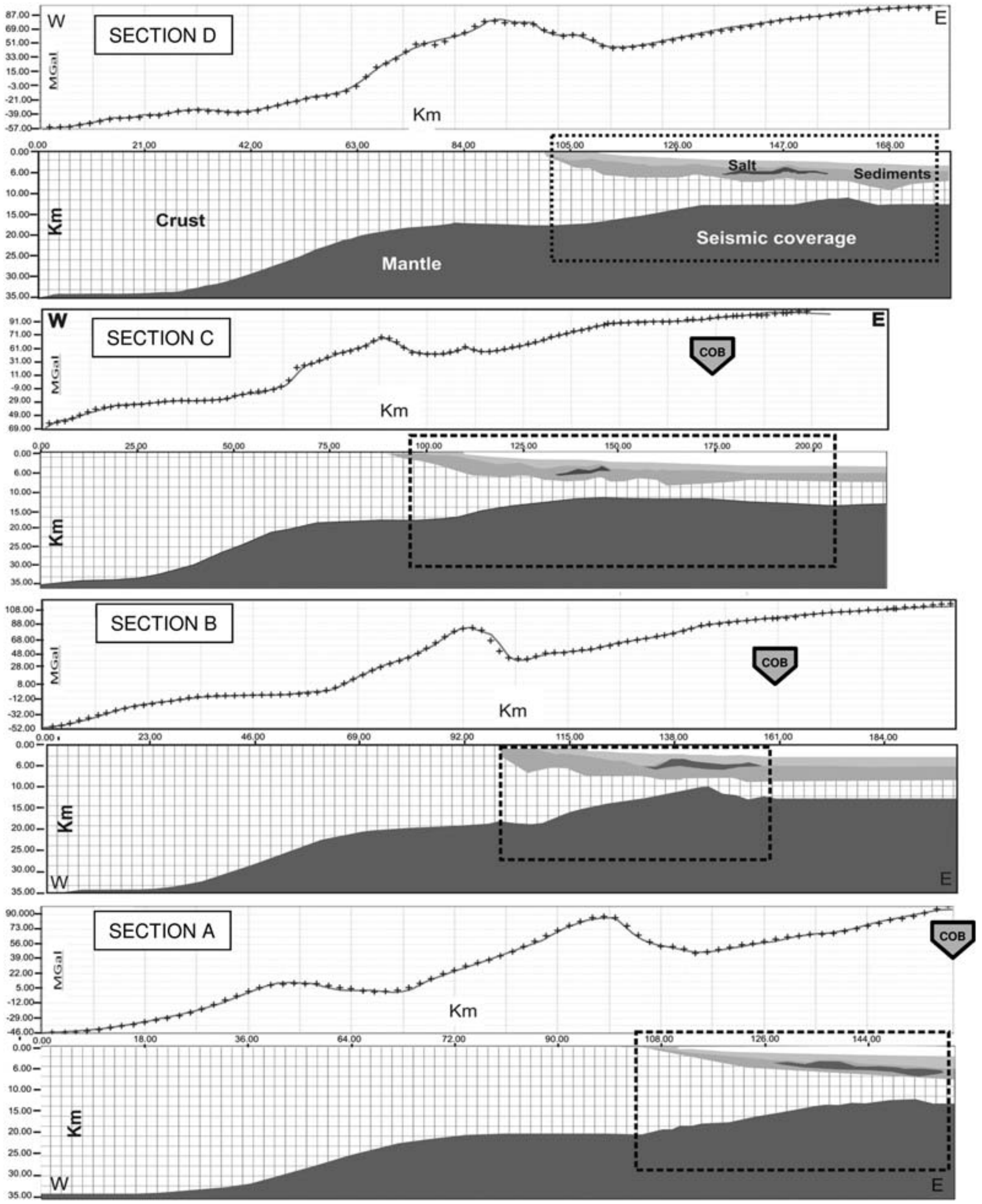

Fig. 6. Modelled sections A–D. The interpretation using interactive forward modelling shows, in the lower panels, the following geological features: mantle (dark grey); crust (checkered pattern); sediments (light grey); and salt (black); and, in the upper panels, the observed (crosses) and fitted (solid lines) gravity anomalies. The latter is produced by the corresponding interpretations shown in the lower panels. The dashed rectangles, shown in the lower panels, indicate the seismic coverage in each section.

Iberia margin: Discovery Working Group 1998; Chian *et al.* 1999). In the Almada Basin, the deep seismic profiles show the progressive thinning of the continental crust to a thickness of 5 or 6 km below the easternmost half-graben (the fifth sub-basin), resulting in a crustal β factor of ±6 before ocean crust developed. The transitional crust indicates a considerable thinning but there is no clear evidence of mantle exhumation, although this mechanism has been proposed to the adjacent Camamu Basin (Caixeta *et al.* 2009). In the seismic example of section C (Fig. 3), it is possible to recognize the high-reflectivity (lower crust) texture below the fifth sub-basin where the maximum crustal stretching is registered. In this area the gravity interpretation (section C, Fig. 6) is compatible with a thin crust having a thickness of the order of 5 km. Therefore, in the Almada Basin, the observed seismic texture and the results of the forward gravity modelling can support a highly stretched transitional crust with the absence of mantle exhumation.

The crystalline basement and crustal inheritance

The Almada basement is part of the southern São Francisco Craton (SSFC), which is primarily composed of Precambrian high- to medium-grade metamorphic rocks and secondarily of low-grade metamorphic facies. The craton was formed by the lateral accretion of orthogneiss terranes during the Archaean and Palaeoproterozoic times through different collisional events, and later was metamorphically re-equilibrated in granulite, amphibolite and, locally, in greenschist facies (Barbosa & Sabaté 2002).

The regional geological framework of the SSFC outcrop comprises, from west to east, three segments known as the Gavião Block, the Jequié Block and the Itabuna–Salvador–Curaça Belt (or Itabunas Belt), with ages becoming progressively younger – from the Archaean to the Palaeoproterozoic – oceanwards (Fig. 7a) (Barbosa *et al.* 2003). The SSFC evolved in three different deformation phases during the Neoarchaean, Palaeoproterozoic and Neoproterozoic times, resulting in a mosaic of complexes, as is observed in the geological map of Figure 7b. According to Barbosa & Sabaté (2002), the geological evidence suggests a collision of the crustal Archaean segments during the Palaeoproterozoic Transamazonian Cycle, resulting in the formation of mountain belts approximately 600 km long and 150 km wide, and with a regional orientation of NNE–SSW. This preferential orientation, NNE–SSW, known as the 'São José' domain (*c.* 2.1 Ga), is composed of elongated granulite metamorphic belts evolved from basic pre- and synorogenic plutonic rocks, and is systematically mapped in the western part of the Jequié Block and in the Itabunas Belt (Barbosa *et al.* 2003). The Palaeoproterozoic collision produced the obduction of the Itabuna Belt onto the Jequié Block and, subsequently, onto the Gavião Block (Barbosa & Sabaté 2002). The structural relationship that the basement terranes exhibit after the Palaeoproterozoic collisional events can be observed in the schematic cross-section of Figure 8, where the basement fabric reflects the orderly development of a high-angle east-dipping thrust fault system. During the Neoproterozoic (696–676 Ma), the southern part of the Itabunas Belt was densely intruded by anorogenic stocks of acid–basic alkaline rocks, known as 'Suite Intrusiva Itabuna', exhibiting a distinctive NE–SW orientation (the Itabunas domain) and representing the last activity recorded in the SSFC during the Precambrian (Barbosa *et al.* 2003).

The significant compositional heterogeneity observed in the São Francisco Craton outcrops has also been recorded in the few wells drilled offshore. In the Almada Basin, at least 10 wells sampled the crystalline basement, in shallow waters, and recovered gneisses (granite, biotite, amphibole and pyroxene composition) as well as granulites with garnet and pyroxene. Mafic and ultramafic enclaves have been reported in the Itabunas Belt of the SSFC, although those compositions were not sampled by the wells drilled in the Almada Basin. However, during the gravity modelling of the crustal section it was necessary to incorporate elongated bodies of gabbros into the basement in order to obtain a better fit between the modelled and the observed gravity (Fig. 6). The regional aeromagnetic map (Fig. 9), the Bouguer gravity map (Fig. 10) and the geological–structural map (Fig. 7b) illustrate the relationship between the basins and the adjacent craton. The three maps capture the structural and compositional effect from the 'São José' and the 'Itabunas' domains, which can be tracked from onshore to offshore positions. The large 3D seismic coverage allowed the detailed mapping of the Almada Basin fault system, which is mainly oriented following the São José domain (NNW–SSE) and is controlled locally by the Itabunas domain (NE–SW), with the generation of few horst structures (Fig. 7b).

The relationship between the basement structure fabric and the rifting process has been studied in detail in the East African Rift (Versfelt 1988, 2010 and references therein; Versfelt & Rosendahl 1989). According to these authors, the pre-existing fabrics exert controls of different magnitude (first to third order) during the initiation and development of the Cenozoic continental rifting. The first order of control is found in the contrast between the craton and the mobile belts, and governs the implantation of the rift zone. The second order of control is exerted by the steep transcontinental strike-slip shear zones, and is responsible for the rift zone kinks and for the major dislocation at the rift axis. Finally, the third order of control corresponds to the mobile belt fabric, and dominates the geometry

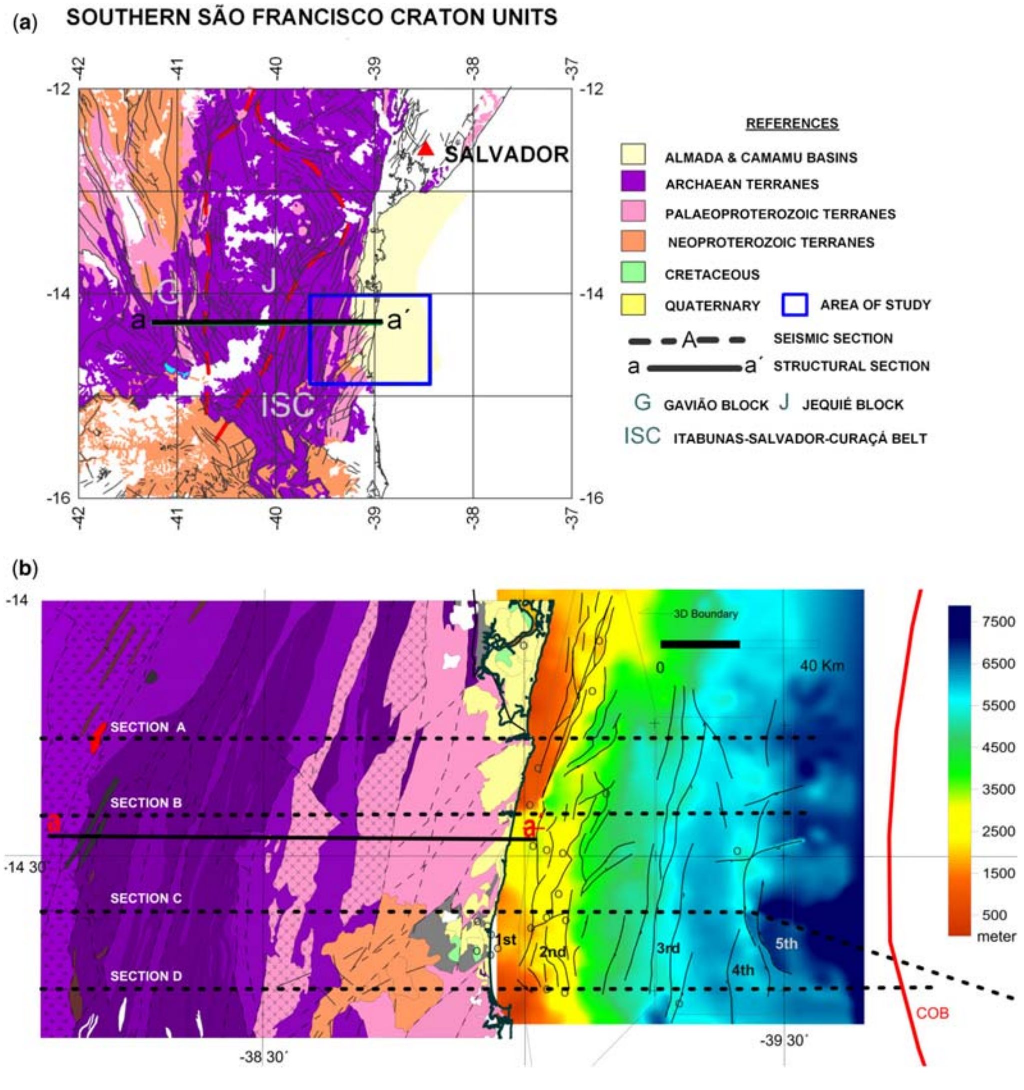

Fig. 7. The crystalline basement structure. (**a**) Regional outcrop map of the São Francisco Craton (after CPRM 2004). (**b**) Composite outcrop geological map (left) and depth seismic structure map (right) of basement units. 1st–5th are the half-graben sub-basins. The red line is the continental–oceanic crust boundary (COB).

of the border faults and the interbasinal fault systems (Versfelt 1988, 2010). The Precambrian SSFC basement fabric contains lithospheric-scale discontinuities that controlled the implantation of the rift zone and the extension style of the Almada Basin during the Mesozoic, as observed in East Africa.

The continent–ocean boundary (COB) and the oceanic basement

The positioning of the COB in divergent margins is highly speculative and can be established by the analysis of different techniques, such as the gradient of the gravity anomaly, magnetic patterns, refraction/reflection seismic studies as well as the location of the post-rift deposits. The eastern limit of the Aptian evaporitic deposits in the East Brazilian margin are reported to be geographically close to the interpreted COB (Davison 1999, 2005; Mohriak 2003).

There are several published proposals for the positioning of the COB in the Almada Basin, all based on satellite-derived gravity analysis. The divergence found among the several COB proposals

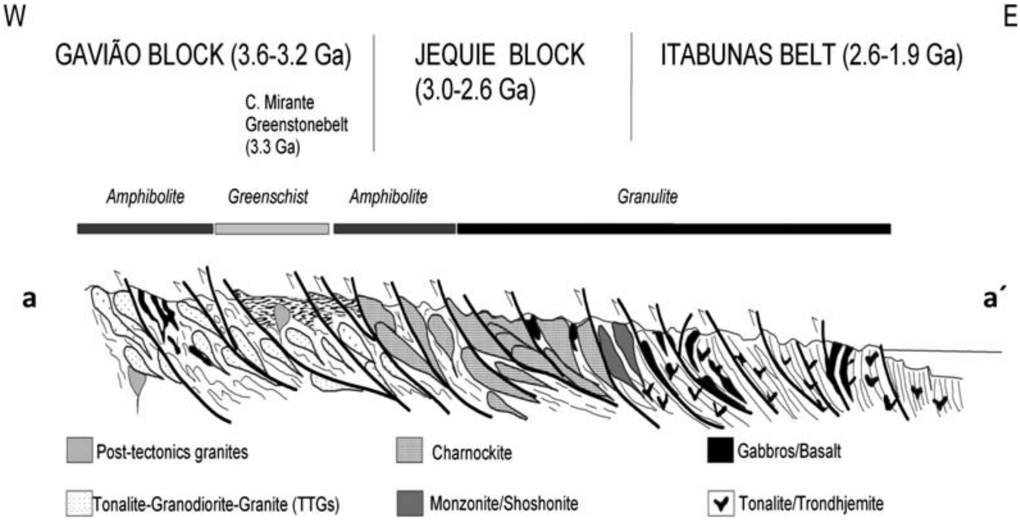

Fig. 8. Schematic west–east cross-sections (a–a′) of the basement fabrics in the southern São Francisco Craton showing the 'São José' domain after the Palaeoproterozoic collision. Location on Figure 7 (Barbosa *et al.* 2003).

may be explained by the absence of any obvious gradient or anomaly response in the gravity or magnetic data of the area close to the ocean–crust boundary. The proposal of Davison (1999) was used in this study and incorporated into the mappings because it shows the best fit to the 2D regional

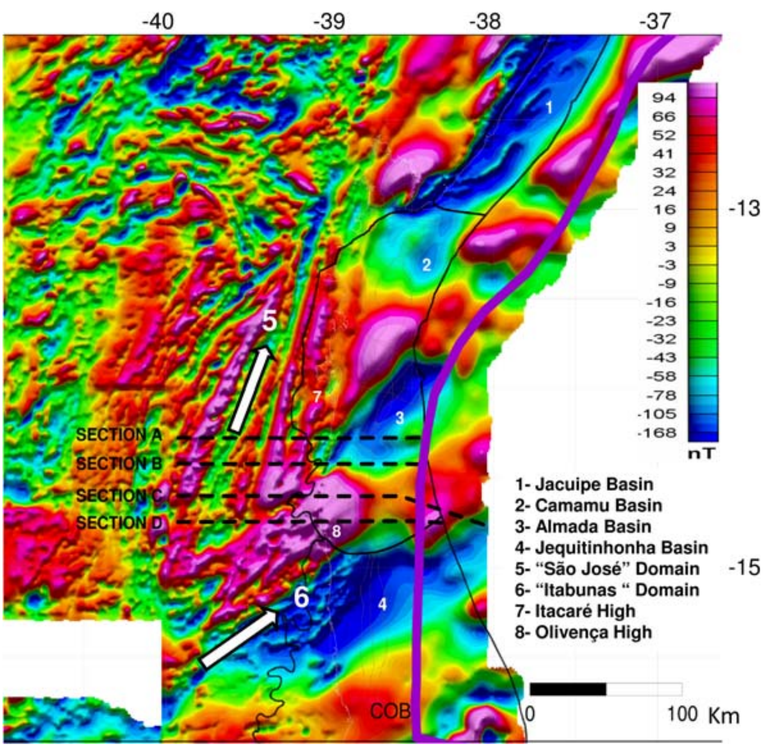

Fig. 9. Aeromagnetic map of the eastern part of São Francisco Craton and the Bahia State basins (CPRM 2004).

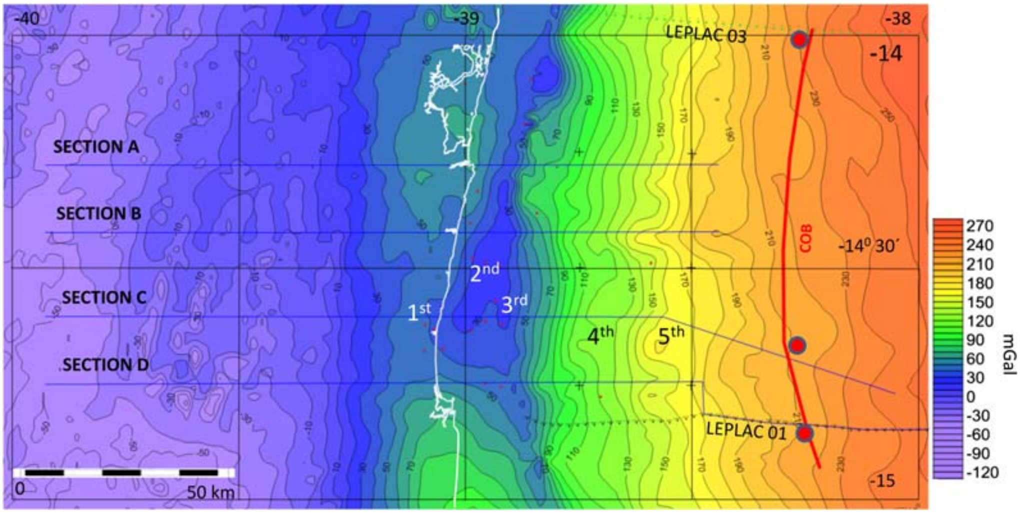

Fig. 10. Regional Bouguer gravity map and the Almada sub-basins. A–D are the selected sections from the 3D survey. LEPLAC 01 and LEPLAC 02 are long 2D seismic profiles. Red dots are the possible crust–ocean boundary checked in the seismic profiles. COB is the ocean–crust boundary obtained from gravity analysis after Davison (1999).

seismic lines (Figs 5, 7b, 9 & 10). The oceanic basement in the Almada Basin exhibits a typical massive seismic texture (Figs 11 & 12); it also frequently shows hyperbolic diffractions on the oceanic basement surface and thicknesses (in time) of the order of 1–2 s that correspond to approximately 7 km (Mohriak *et al.* 2002).

To the north of the area of study, in the basins of Jacuípe and Sergipe (Fig. 1b), major NW–SE-trending seamount groups, the Bahia Seamounts, are seen in the bathymetric and gravity maps. The Bahia Seamounts are comprised of at least 40 elevations from 1000 to 1700 m high that cover an area of approximately 125 000 km^2. Radiometric and palaeomagnetic results were obtained from analyses of dredge samples that indicate an Upper Cretaceous age for the oceanic basalts, ranging from 78 to 62 ± 4 Ma. This Upper Cretaceous

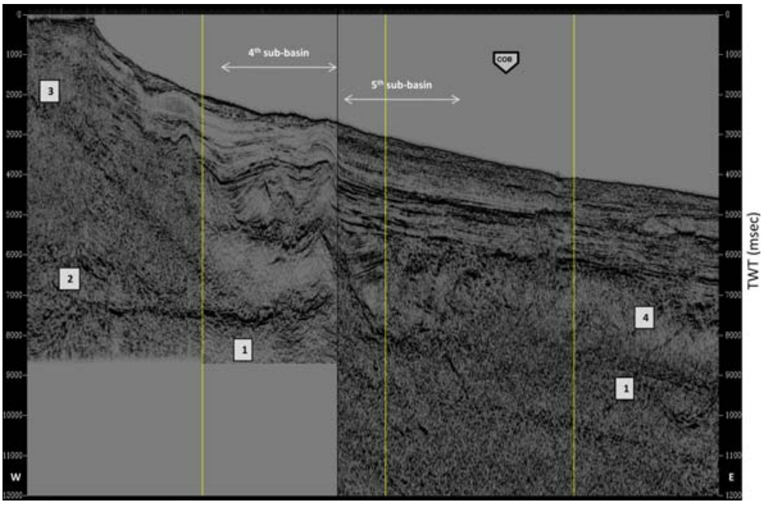

Fig. 11. Composite (2D and 3D) seismic section C displayed in reflection strength attribute. Seismic textures: (1) Moho; (2) lower crust; (3) upper crust; and (4) ocean crust. Reproduced courtesy of PGS do Brasil and ANP.

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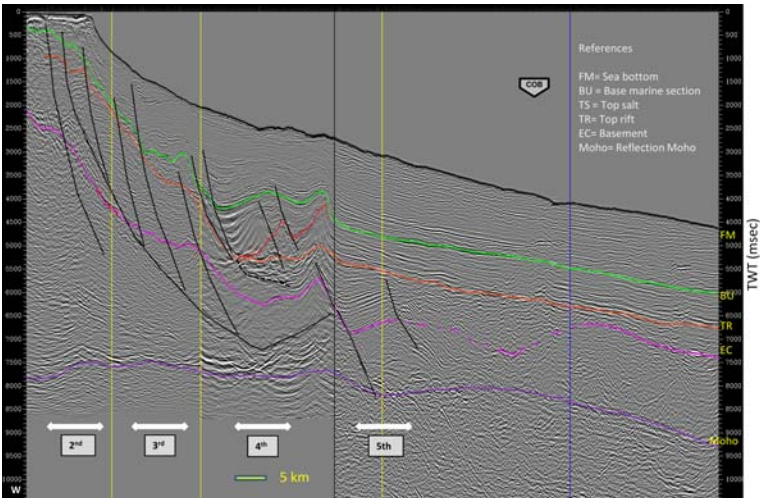

Fig. 12. Seismic section C (in regular amplitude display and with interpretation). 2nd–5th are the half-graben sub-basins. Reproduced courtesy of PGS Brasil and ANP.

magmatism has been related to the activity of a hotspot during the post-rift stage (Cherkis *et al.* 1992; Bryan & Cherkis 1995).

The geological evolution

The Berriasian–Aptian rifting process produced a complex structural framework with the creation of at least five NNE–SSW-striking half-graben sub-basins (right-hand panel in Fig. 7b). The development from onshore to deep-water offshore of these sub-basins can be interpreted from both seismic and gravity data (Figs 7b & 10). The Bouguer gravity map (Fig. 10) shows the development of the first–third sub-basins, from west to east. The fourth and fifth depocentres have only a mild gravity expression, probably due to the abrupt mantle rise. Conversely, the fourth and fifth can be seen in the time structure map of the basement relief (right-hand panel in Fig. 7b), as well as in the seismic examples of Figures 3, 4, 11 & 12 (Gordon 2011).

The good quality of the seismic images permitted the recognition of a major listric fault system that cut the upper crust, linking the half-graben sub-basins, and apparently detaching onto the lower crust. This is shown in the seismic examples of Figures 12–15, displayed in regular amplitude attribute and with interpretation. The 3D seismic profiles also support the interpretation of the spatial continuity of the master fault, as well as the way in which the synthetic subsidiary faults are connected to the master fault. This mechanism results in a regional eastward-dipping whole-crust detachment surface. In the Almada Basin, the detachment surface tends to sole near the base of the crust, although, locally, the listric fault system may be offsetting the reflection Moho discontinuity (Figs 3, 11 & 14). The low-angle syn-rift faults (simple shear or detachment model) have been documented in outcrops of the Italian Alps crust (Froitzheim & Manatschal 1996; Hermann *et al.* 1997) and commonly imaged in seismic profiles in several non-volcanic margins, such as the Iberian margin (Bowling & Harry 2001 and references therein).

The Almada Basin crustal profile exhibits an asymmetric break-up compatible with the simple shear rifting model or with variations of this model such us the ‘delamination and subcrustal pure shear model’ (Wernicke *et al.* 1985; Lister *et al.* 1986). This rifting mechanism is able to accommodate large amounts of crustal thinning before break-up. This extensional model has also been proposed to explain the asymmetric distribution of syn-rift depocentres and the lack of magmatism in the NVM (Lister *et al.* 1986; Buck *et al.* 1988).

A remarkable general characteristic of the Almada Basin, as already mentioned, is the absence of the magmatic activity that preceded and/or accompanied the formation and early evolution of most of the basins that form the South American margin (SAM). This characteristic contrasts with the common behaviour of the SAM in which the active/passive magmatic mechanisms (in the sense of Courtillot *et al.* 1999) resulted in the generation of several of the largest igneous provinces in

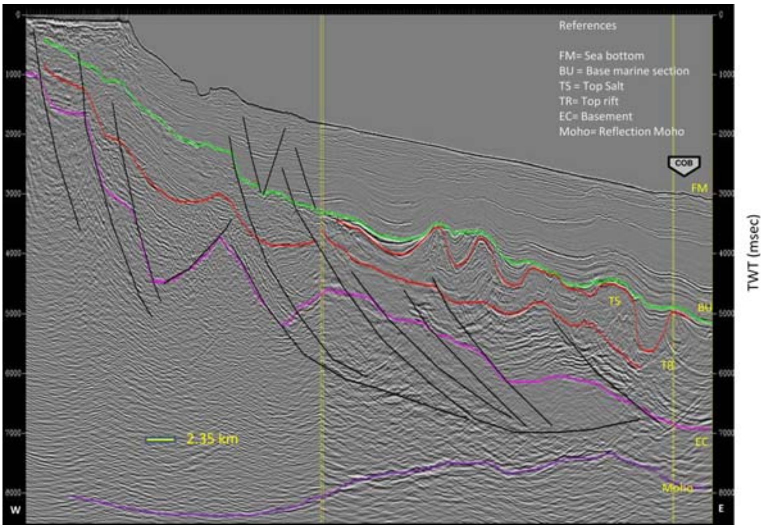

Fig. 13. Seismic section A (in regular amplitude display and with interpretation). Reproduced courtesy of PGS do Brasil.

the world (e.g. Chon Aike and Paraná), as well as minor magmatic provinces (e.g. Cabo Santo Agostinho in NE Brazil), important intrabasin volcanism and large volumes of seaward-dipping reflectors (SDRs) (Fig. 1a). In the vicinity of the Almada Basin, regional and detailed onshore mapping surveys conducted by CPRM and other Brazilian institutions have not provided any evidence of magmatic rocks related to the syn-rift process.

To date, more than 42 300 wells have been drilled in the 18 basins that form the SAM and many of them sampled syn-rift magmatic rocks in the basins. Notwithstanding, none of the 28 wells drilled in the Almada Basin have shown evidence of syn-rift volcanism.

The existence of SDRs has been reported north and south of the southern Bahia State segment, as seen in Figure 1a (Mohriak *et al.* 1998, 2000,

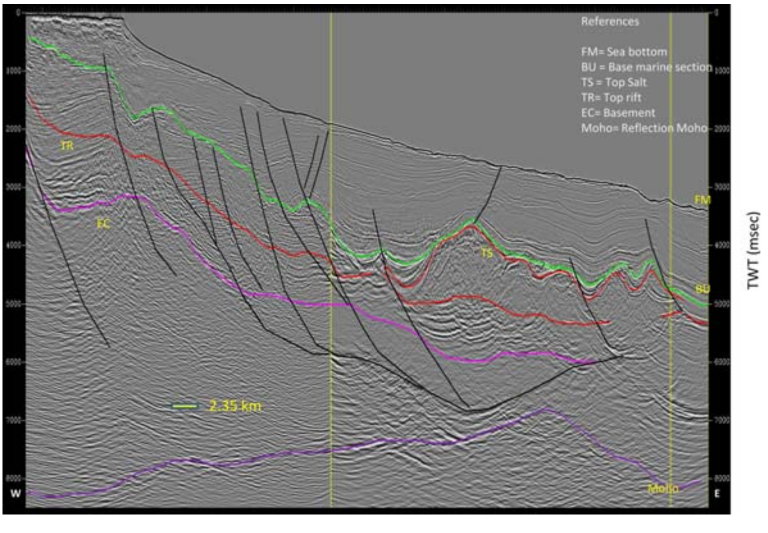

Fig. 14. Seismic section B (in regular amplitude display and with interpretation). Reproduced courtesy of PGS do Brasil.

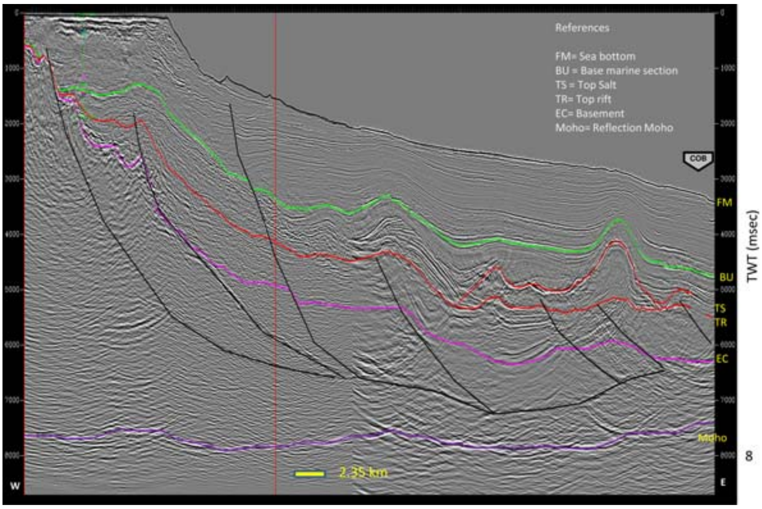

Fig. 15. Seismic section D (in regular amplitude display and with interpretation). Reproduced courtesy of PGS do Brasil.

2002; Franke *et al.* 2007). However, the deep seismic profiles of the Almada segment display the development of normal oceanic crust without important manifestations of volcanism during and subsequent to the main rift stage. In the Almada Basin, the area between the pure oceanic crust and the fifth sub-basin is of the order of 10 km wide with very subtle disclosure of bright reflectors indicative of volcanic layers dipping oceanwards. The absence of SDRs is also demonstrated by the response of the magnetic anomalies. In the Almada Basin, the distribution of magnetic anomalies reflects the control of the basement structures, following that of the Itabunas domain (Fig. 9). This magnetic pattern behaves differently from the Jacuipe Basin; for example, where wedges of SDRs can be recognized in seismic sections, creating a 'parallel to the coast' magnetic anomaly distribution (Mohriak *et al.* 1998). This observation allowed us to conclude that in this segment, SDRs are absent or are volumetrically insignificant.

The conjugate margin in West Africa

The southern Gabon Basin in West Africa corresponds to the conjugate margin of the Almada and Camamu basins in eastern Brazil. A palinspastic reconstruction at 118 Ma of the South American and West African plates was elaborated, using GPLATES software (www.gplates.org; Boyden *et al.* 2011; Gurnis *et al.* 2012), and CPRM and CCGM (Commission de la Carte Géologique du Monde) geological maps of Brazil and Africa (after Bassot 1988; Teisserenc & Villemin 1989; CPRM 2004; Schlüter 2007; CCGM 2010) as shown in Figure 16. This reconstruction for Aptian times represents the early drift phase where early oceanic crust was developed and indicates a large asymmetric continental break-up. The initial spreading ridges were located closer to the Brazilian coastline, causing a wider rift in the Gabon margin. A gross estimation indicates that the Almada Basin reached a maximum width of the order of 120 km while the southern Gabonese counterpart achieved a width in the range of 400 km (Fig. 16).

The tectonic setting of the South Gabon Basin (SGB) was determined by several key elements such as the N'Komi Fracture Zone, the Chaillu Massif, the Ogooué Orogenic Belt, the Mayombe Fold Belt and the Nyanga Basin, as seen in Figure 16 (Bassot 1988; Teisserenc & Villemin 1989; Schlüter 2007).

The N'Komi Fracture Zone is a dextral wrench fault system that separates the northern and southern Gabon basins, creating segments with different -geological evolution. Refraction studies evidence depths to the basement of the order of 12 and 9 km in the northern and southern segments, respectively; and strong magnetic and gravity anomalies are also recognized along the fracture zone (Teisserenc & Villemin 1989). The N'Komi fracture exhibits a good match with the Barra Fracture Zone in the Brazilian margin (Fig. 16). The Barra wrench fracture zone is the boundary separating the basins of Camamu–Almada, Jacuípe and the aulacogen of the Recôncavo Basin. The Barra Fracture Zone is a strike-slip fault system, as is demonstrated in

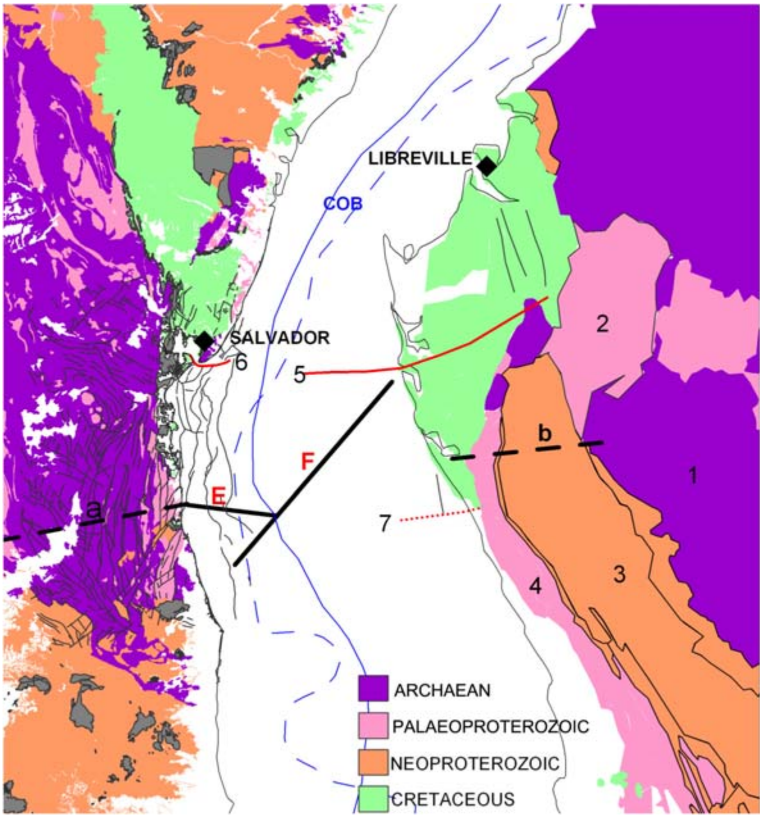

Fig. 16. Possible South American and West African plate configuration at the early drift phase (model at 118 Ma). Legend for numbers and letters assigned to sections and major structural elements: a, basement structural profile in the southern São Francisco Craton across the São José domain (Fig. 8); b, basement structural profiles in the southern Gabon (Fig. 18); E, deep seismic lines in the south of the Almada Basin (displayed in Figs 11, 12 & 17); F, deep seismic lines that correspond to the seismic line, Probe 23, in the southern Gabon (Fig. 17). Precambrian West Africa terranes: 1, Chaillu Massif (Congo Craton); 2, the Ogooué orogenic belt; 3, the Nyanga Basin; 4, the Mayombe Fold Belt; 5, N'Komi Fracture Zone; 6, Itaparica Fracture Zone; 7, Mayumba Spur. The dash and continuous blue lines are the ocean–crust boundary (COB) of West Africa and Brazil, respectively. Reconstruction was performed using GPLATES software (www.GPLATES.org) and geological maps (after Bassot 1988; Teisserenc & Villemin 1989; CPRM 2004; Schlüter 2007; CCGM 2010).

seismic profiles, and also exhibits conspicuous gravity anomalies. The wells drilled north and south of this fracture zone, in Itaparica Island, display large differences in the sedimentary thickness (Jonas 2009).

The Cretaceous rift sequences of the South Gabon Basin (SGB) lies on a NW–SE-trending suture zone that extends along the SW side of the Archaean Chaillu Massif (Congo Craton: Teisserenc & Villemin 1989). The SGB basement is composed of different Palaeoproterozoic and Neoproterozoic rocks, and was affected later by the tecto-thermal Pan-African orogeny (Kröner & Stern 2004). The Palaeoproterozoic units are located east and SE of the SGB, and are known as the Ogooué Orogenic Belt and the Mayombe Fold Belt. The Ogooué is composed of a number of thrust nappes of highly deformed, medium- to high-grade metasedimentary and metavolcanic rocks. The Mayombe is formed by medium- to high-grade migmatites, post-tectonics granites and metasedimentary rocks. The Neoproterozoic is represented by the Nyanga Basin and is composed of thick low-grade deformed volcano-sedimentary sequences. The Pan-African orogeny overprints an east-verging deformation during the Neoproterozoic, resulting in the formation of the West Congolian Belt. The deformation consisted, from west to east, of the low-angle thrust of the allochthonous thrust-and-fold stack terrane of the Mayombe Fold Belt onto the

Nyanga Basin, and then its subsequent thrusting onto the Congo Craton (Figs 17 & 18) (Bassot 1988; Kröner & Stern 2004)

A geoseismic transect based on seismic profiles from both the Brazilian side and the African side (profiles E and F, respectively, in Figs 16 & 17) indicates several important similarities and differences between the crustal architecture and the sedimentary development of the two margins. We interpret the transition from the lower crust to the upper mantle (Moho discontinuity) at around 9–10 s in the platform of both margins. The base of the crust is marked by a strong reflectivity, which is indicative of underplating or mafic layering at the transition from lower crust to upper mantle. An outermost high is interpreted in both margins, coinciding approximately with the ending of the salt deposits, but the magnetic signature of volcanic intrusions in the crust is strongest in the Gabon Basin.

A comparison of the stratigraphic records of the Almada and South Gabon basins is provided in Figure 2 (after Logar 1983; Teisserenc & Villemin 1989; Gontijo *et al.* 2007). The rift structure in the southern Gabon Basin is characterized by wide and deep sedimentary depocentres below the sag basin (with the rich source rock of the Melania Formation) and also by the Aptian evaporites (Ezanga Formation). In the Brazilian side, the basement is affected by several small normal faults from the rift border down-stepping towards the platform. Near the shelf break, a major extensional fault offsets the basement and controls the formation of a thick salt basin in deep waters (Taipus Mirim Formation). The rift in deep water is highly rotated and eroded towards the continent–ocean boundary, similar to the Jacuípe Basin (Mohriak *et al.* 1995, 2000). Volcanic rocks are only interpreted beyond the salt basin, and these are overlain by Aptian–Albian sedimentary layers in the oceanic crust. A very thick Tertiary–Quaternary sedimentary sequence is observed in the deep water of the Gabon Basin (Ozouri, Animba and Mandorove formations), probably related to sediment input from the Ogooue Delta. These differences suggest an asymmetric rifting process, probably related to a different crustal fabric, with a much wider rift and salt basin on the African side.

The Almada Basin crustal fabric, as previously discussed, is characterized by Palaeoproterozoic granulites in a high-angle east-dipping thrust fault regime (Fig. 8), whereas the southern Gabon Basin crustal fabric is distinguished by low- to medium-grade metamorphic rocks in a low-angle thrust tectonic regime (Fig. 18).

The Almada and South Gabon basins are also characterized by a lack of any substantial volcanism

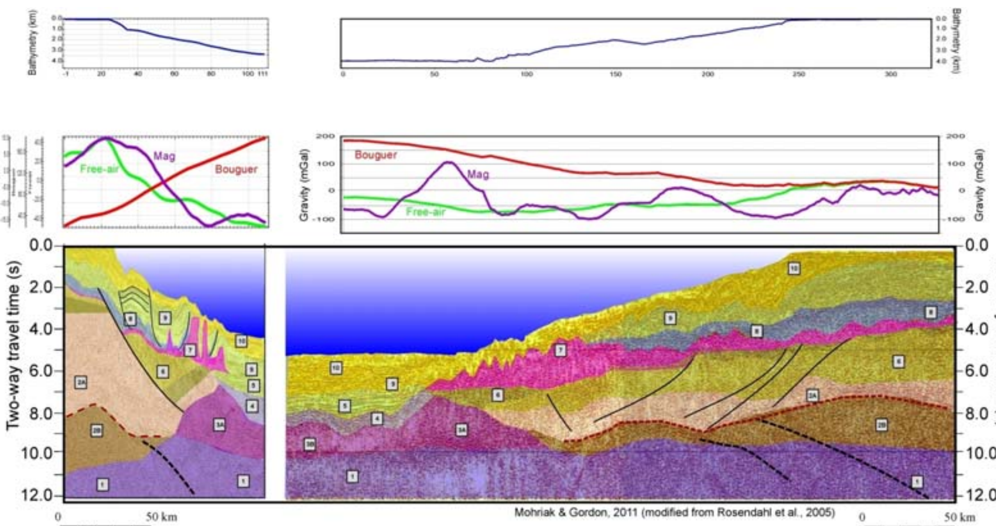

Fig. 17. Geoseismic transects from the Brazilian and West African conjugate margins (profiles E and F, respectively, location in Fig. 16). Potential field data (Free-air, Bouguer and magnetic data from public datasets) are plotted above the seismic profiles. The simplified bathymetry profile is based on the GEBCO dataset. Legend for numbers assigned to major structural and stratigraphic elements: 1, upper mantle; 2, continental basement (2A, upper crust; 2B, reflective lower crust/underplating); 3, igneous crust (3A, outermost high with highly intruded basement; 3B, basalts/oceanic crust); 4, Aptian–Albian sedimentary sequences overlying volcanic basement; 5, Upper Cretaceous sedimentary sequences overlying volcanic basement; 6, pre- and syn-rift sequences; 7, Aptian salt; 8, Albian–Turonian carbonates and shales; 9, Upper Cretaceous–Early Tertiary; 10, Tertiary–Quaternary sedimentary sequences.

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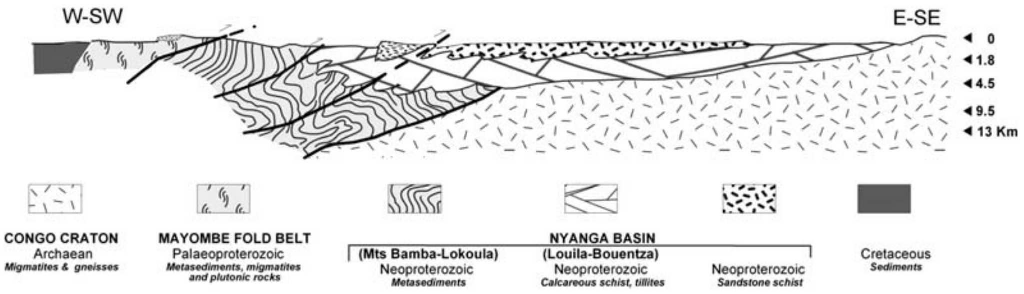

Fig. 18. Schematic WSW–ESE cross-sections of the basement fabrics in the west of the Congo Craton (Chaillu Massif), the Nyanga Basin and the Mayombe Fold Belt (after Bassot 1988), location on Figure 16.

during the rift phase. However, the transition to oceanic crust (proto-oceanic phase) is marked by the emplacement of igneous intrusions in the crust and the basalt flooring of the Aptian–Albian sedimentary layers. Locally, extensional faults are observed in the proto-oceanic crust, indicating that extensional stresses were affecting the regions adjacent to the embryonic spreading centres.

Geotectonic implications in the origin of the Almada segment

The mechanisms responsible for the generation and emplacement of the large amounts of magma recorded in the divergent margins are still controversial and subject to intense discussion in the Earth Sciences. The changes in pressure and temperature, which are necessary to produce the magma melts from mantle rocks, can be the result of lithospheric thinning (adiabatic decompression) or mantle plumes (thermal anomalies). Along the South American segments, both lithospheric thinning and mantle plume models have been proposed as possible mechanisms for magma generation. Alternatively, the combination of these two mechanisms seems to have played a significant role in the margin evolution, as proposed by Courtillot *et al.* (1999), in the passive/active rifting model.

Several mechanisms have been put forward for consideration in the geological literature in order to explain the origin of the non volcanic margins (NVM); for example, the presence of a 'cool mantle', a 'simple shear rifting' and the extension of a 'rheological homogeneous crust', among other hypotheses (Bowling & Harry 2001). These authors have concluded that the hypothesis of a cool mantle is difficult to reconcile with the presence of a normal oceanic crust with a thickness of the order of 7–10 km. The creation of oceanic crust requires that a relatively warm mantle ascends to shallow depths during the late stages of extension (Bowling & Harry 2001). In the Almada Basin, the presence of a normal oceanic crust has been observed next to the younger rift sub-basin (the fifth sub-basin).

In the Almada Basin (and also in the adjacent Camamu Basin), crustal-scale detachment faults are imaged in the deep seismic profiles. The detachment mechanism can result in a large amount of crustal stretching without requiring a large thinning of the lithospheric mantle. As a result, the rising of asthenospheric mantle is minimized and syn-extensional melt production is inhibited (Lister *et al.* 1986).

According to Bowling & Harry (2001), the finite-element numerical modelling of continental rifting could explain the formation of NVM as a result of the extension of a rheologically homogeneous crust. In these geological conditions, lithospheric necking does not appear until a very late stage of the rifting phase, and cool mantle conditions are not required. The duration of the syn-rift melting episode seems to be controlled by the extension rate; a higher extension rate promotes a shorter period of melt production. Parameters like the initial crustal thickness, the extension rates and the distribution of pre-existing rheological heterogeneities in the crust (the basement structural inheritance) may have controlled the duration of the rifting and the geometry of the margin after the continental break-up. For these authors, most of the known volcanic margins (VM) occur in areas in which the crustal heterogeneity can be attributed to the contrast between the strength of the rocks within the Palaeozoic orogenic belts and the adjacent Precambrian basements. A comparison of the spatial distribution of VM and NVM in the North Atlantic with the age of the basements suggests that the contrast between Precambrian and Phanerozoic crusts provides sufficient heterogeneity to promote volcanic rifting. However, if the suture area lies far from the rift axis the crust can behave in a homogeneous way, promoting the development of NVM (Bowling & Harry 2001). In the southern of

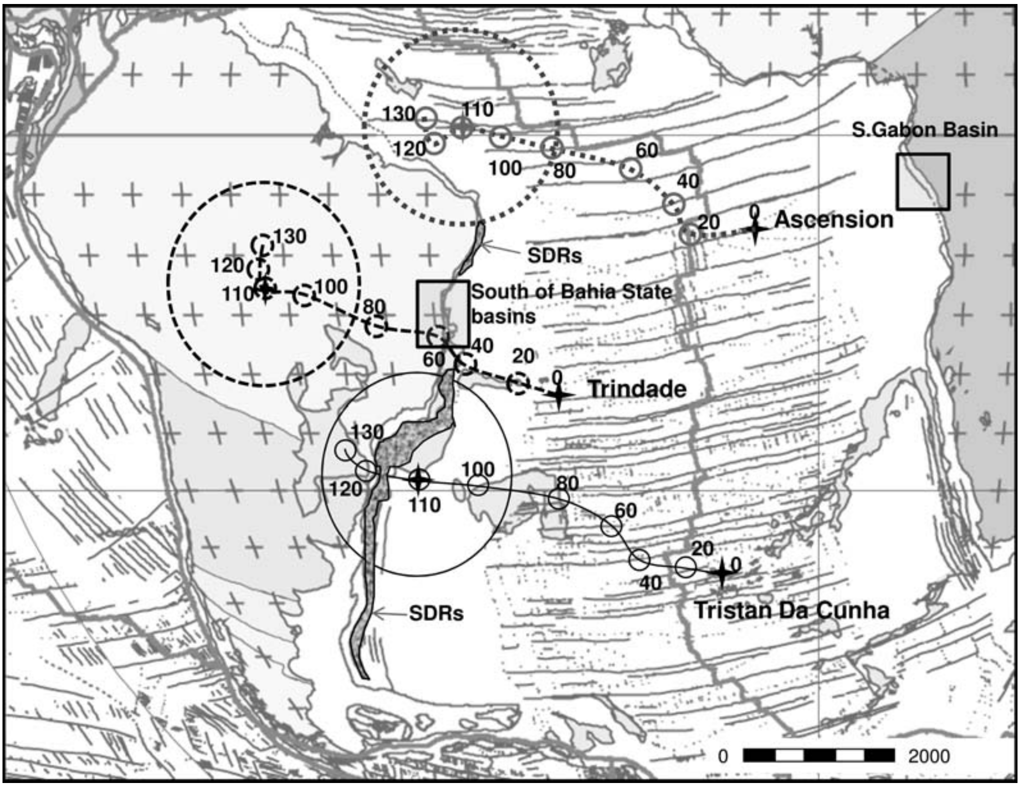

Fig. 19. Possible South Atlantic hotspot trajectories for the last 130 Ma for the South American margin (after Lawver *et al.* 2004). The circles, 2000 km in diameter, represent the area of influence for the hotspot candidates of Ascencion, Trindade and Tristan da Cunha.

the Bahia State basins segment, the basins are developed over the Archaean–Palaeoproterozoic crusts of the São Francisco Craton (Fig. 7a, b). Although the craton is petrographically heterogeneous, the crust was re-equilibrated during the granulite-facies-grade metamorphism.

The absence of large igneous provinces (LIPs) in the onshore vicinity of the Almada Basin can be explained by the distal location of this segment from the area of influence of the known South Atlantic hotspots of Tristan, Trindade and Ascension during the early Cretaceous, according to the palaeogeographic reconstructions of Lawver *et al.* (2004) and as presented in Figure 19.

Conclusions

This article has focused on the crustal architectural elements of the Almada Basin in NE Brazil compared to its conjugate margin in West Africa, the South Gabon Basin. The following conclusions can be drawn from this study.

- The good quality 3D seismic allowed: (a) the interpretation of a strong reflector probably related to the discontinuity between the lower crust and the upper mantle (reflection Moho); and (b) the recognition of the seismic facies that are characteristic of upper mantle, lower and upper continental crust, and the oceanic crust.
- The deep seismic profiles and the 2D gravity forward modelling, in conjunction, indicate an important crustal stretching without clear evidence of mantle exhumation.
- The Almada Basin crustal fabric is characterized by Palaeoproterozoic granulites in the high-angle east-dipping thrust fault regime of the São José domain of the Itabunas Belt, whereas the southern Gabon Basin crustal fabric is distinguished by low- to medium-grade metamorphic rocks in the low-angle thrust tectonic regime of the West Congo Belt.
- The inherited basement structures controlled the generation and development of the Almada/Camamu and South Gabon basins. The pre-existing basement structures governed: (a) the

implantation of the rift zone, probably at the junction between the Itabunas Belt and the West Congo Belt; (b) the N'Komi and Barra fracture zones; and (c) the Almada and South Gabon intra-basinal fault systems.

- The large whole-crustal listric faults and the generation of the half-graben sub-basins observed in the Almada seismic profiles suggest an asymmetric break-up. The basin asymmetry was probably driven by either a simple shear mechanism or a variation, such as the crustal delamination and depth-dependent stretching with pure shear mechanism.
- The rift asymmetry in the conjugate margins is indicative of a preferential emplacement of the embryonic spreading centres near the Brazilian margin.
- During the break-up process, the Almada segment appears to behave as the lower plate, resulting in a narrow basin with limited salt and syn-rift deposits. Conversely, the Gabonese counterpart seems to act as the upper plate, leading to the development of a wider rift with significant salt and syn-rift deposits.
- A deficiency of pre- and syn-rift magmatism is observed in both the Almada and the South Gabon basins. In the Almada segment the non-volcanic character is expressed by the lack of onshore volcanism, basinal volcanism and seaward-dipping reflector wedges.
- The absence of volcanism in the syn-rift sequence can be explained by the large distance from the known hotspot candidates in the South-Atlantic Ocean. The non-occurrence of seaward dipping reflectors (SDR), or the presence of volumetrically inexpressive SDRs, could be related to a rheological homogeneous crust in extension. In addition, some form of rifting mechanism could have accommodated a large crustal extension decoupled from the lithospheric thinning.

Although the South Atlantic margin is mostly volcanic, the presence of the non-volcanic Almada and South Gabon segments is important as a record of the differences in the geotectonic processes that account for the formation of these segments.

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