Development history of the southern terminus of the Central Atlantic; Guyana–Suriname case study

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Abstract: The study focuses on the offshore Guyana–Suriname–French Guiana region. It draws from seismic, well, gravimetric and magnetic data. They indicate that the continental break-up along the western margin of the Demerara Plateau took place during the Callovian–Oxfordian, associated with the Central Atlantic opening, and accommodated by normal faults. The continental break-up in the SE offshore Guyana accommodated by strike-slip faults was coeval. The continental break-up along the NE and eastern margins of the Demerara Plateau took place during the late Aptian–Albian, associated with the opening of the Equatorial Atlantic, and accommodated by dextral strike-slip and normal faults, respectively.

Different spreading vectors of the Central and Equatorial Atlantic required development of the Accommodation Block during the late Aptian/Albian–Paleocene in their contact region, and in the region between the Central Atlantic and its southernmost portion represented by the Offshore Guyana Block, which were separated from each other by the opening Equatorial Atlantic. Its role was to accommodate for about 20’ mismatch between the Central and Equatorial Atlantic spreading vectors, which has decreased from the late Aptian/Albian to Paleocene down to 0’.

Differential movements between the Central and Equatorial Atlantic oceans were also accommodated by strike-slip faults of the Guyana continental margin, some active until the Paleocene.

Supplementary material: Extended methods and discussion chapters are available at http://www.geolsoc.org.uk/SUP18875

There are numerous places where one can study a deformation history of the ocean segment terminus, a point where the ocean opening was arrested for a certain period of time, forming a triple junction. The Central and Northern Atlantic oceans had a number of terminuses lasting for a certain period

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of time. This is indicated by their segments being opened in a general direction from south to north during different periods of time (e.g. Müller et al. 1997; Withjack et al. 1998; Le Roy et al. 2004; Schettino & Turco 2009; Labails et al. 2010; Seton et al. 2012). For example, the break-up unconformity is as old as the Hettangian–Toarcian and Hettangian–Pliensbachian in the conjugate Georges Bank and Tarfaya basins, respectively (Davison et al. 2002). It is Aalenian in the Scotian Basin (Cloetingh et al. 1989; Tankard et al. 1989; Welsink et al. 1989), although Wade & MacLean (1990) inferred the Sinemurian–Toarcian age. The age of unconformity in the d’Abda Basin is Toarcian–Aalenian and as young as the Callovian northwards (Aajdour et al. 1999; Echarfaoui et al. 2002). Magnetic data from the Central Atlantic segment connecting Nova Scotia and central and NW Morocco indicate that the drifting started here either before 175 Ma (Bajocian–Bathonian) or 191 Ma (Toarcian) or even 195 Ma (Pliensbachian) (Klitgord & Schouten 1986; Srivastava & Tapscott 1986; Verhoef & Srivastava 1989; Sahabi et al. 2004). The seafloor spreading centres subsequently propagated further northwards. Drifting began between Newfoundland and Iberia in the Early Cretaceous, between Labrador and western Greenland in the Late Cretaceous or Paleocene, and between eastern Greenland and NW Europe in the early Eocene (e.g. Srivastava & Tapscott 1986; Srivastava & Verhoef 1992; Chalmers & Laursen 1995).

One of the most interesting terminuses is a triple junction that started to exist during the Rhaetian–Sinemurian at the southern end of the Central Atlantic. It was coeval with magmatism of the Central Atlantic Magmatic Province (CAMP). Plate reconstructions (e.g. Scotese 1998; Golonka 2000; Schettino & Turco 2009; Labails et al. 2010) and regional syntheses (Cornet & Olsen 1985; Withjack et al. 1998; Le Roy & Piqué 2001; Olsen et al. 2002; Ellouz et al. 2003; Nemčok et al. 2005; Hafid et al. 2008) indicate that the Central Atlantic opening must have started here and propagated towards the north. While the basalt horizons of the CAMP postdate the synrift faults in the southern portion of the Central Atlantic Rift System, they are cut by synrift faults in the north (e.g. McHone 2000). Accordingly, the dykes are oblique to the rift units in the south (e.g. Thayer 1970; Randazzo & Copeland 1976; Bain & Harvey 1977; McHone 1988), post-dating both normal fault activity and basin-fill tilt, while the dyke systems are parallel to rift units in the north.

The first of the three arms of this triple junction, the failed one located in the future Equatorial Atlantic region, must have undergone only a minimal extension. The only evidence of its existence comes from the NW–SE-striking dykes, which are 197–203 myr old, in Mali, Guinea, Sierra Leone, Liberia, Ivory Coast and the Guyana Shield (e.g. Behrendt et al. 1974; Fodor & McKee 1986; Gibbs 1986; Venkatakrishnan & Culver 1989; De Azevedo 1991), and the sedimentary fill of the Marajo Basin in Brazil (de Matos 2000). The second arm, represented by the Central Atlantic Rift System, has reached a continental break-up. Evidence of its existence come from NE–SW-trending rift units with well-dated fill from both conjugate margins of the Central Atlantic (e.g. Swanson 1986; Olsen et al. 1991, 2003; Schlische 1993, 2003; Withjack et al. 1998; Le Roy & Piqué 2001; Schlische & Withjack 2005; Olsen & Et-Touhami 2008). The third arm was dominated by sinistral strike-slip faulting. It ran for about 2000 km west, to the Gulf of Mexico region (e.g. Seton et al. 2012 and references therein). The evidence for its existence include:

- Seismically imaged faults of the Western Florida coast, which are similar to the Bahamas Fracture Zone (Dobson & Buffler 1997; Denman & Adamick 2000).
- The Bahamas Transfer Zone located to the east of the western Florida strike-slip fault, both of them sandwiching western Florida and being a part of the strike-slip transfer between the Central and Southern Atlantic (Debalko & Buffler 1992).
- Other similarly trending strike-slip faults further westwards of those mentioned, which provide transfer faulting between individual rift zones of flip-flopping polarities inside the Gulf of Mexico sensu stricto (Simmons 1992; Watkins et al. 1995).

The post-Sinemurian development of this triple junction and its surrounding region, interpreting the data from offshore Guyana and Suriname, is the focus of this study. The study area (Fig. 1) provides a unique setting where one can see the ocean segment end located right next to the continental lithosphere. In this case, the entire deformation record of the ocean terminus is in place where it is not overprinted by a deformation record associated with the break-up of its continental side. It is here where we study the deformation history, drawing from robust reflection seismic data, 39 wells, an age map of the oceanic crust (Müller et al. 1997), and original gravity and magnetic data.

Our first goal is to interpret the boundaries of blocks formed by different crustal types and to determine the age of their crust. The secondary goal is a definition of their structural architecture, including kinematics and activity time periods. Relying on the cross-cutting relationships of structures, the final goal is to restore the deformation history of
Fig. 1. (a) The free-air gravity-anomaly map. The thin black line indicates the boundary of the Accommodation Block, which is also shown by the semi-transparent free-air gravity image. The black arrow points at one of the roughly east–west-trending flow lines in the gravity image. The rectangle shows the location of the study area (and the location of b and Fig. 5a, b, c). AB, Accommodation Block; CA, the main body of the Central Atlantic; D, Demerara Plateau; G, the Guyana continental margin segment; GP, Guinea Plateau; GSG, the Guyana–Suriname–French Guiana continental margin; EA, Equatorial Atlantic; ofz, oceanic fracture zone; OGB, Offshore Guyana Block.
the ocean segment terminus, which prevented the ocean from further propagation without an offset. For simplicity, all geographical orientation data, palaeostress vectors and palaeospreading vectors are given with respect to present-day coordinates throughout the paper.

Geological setting

The age of the oceanic crust building the Offshore Guyana Block (see Fig. 1 for the location) is relatively unknown. Magnetic anomaly studies (Müller et al. 1993, 1997, 2008) suggest an Aptian–Santonian age (Fig. 2). Reflection seismic images and wells available from the public sector are not deep enough to provide the exact age of this crust (e.g. Staatsolie 2001, 2009) (Fig. 3). The Lower Jurassic–Lower Cretaceous strata have been found on the Guyana continental margin (e.g. Davison et al. 2002; Yang & Escalona 2011), and are assumed to be structural remnants of pre-existing Central Atlantic rift units. The Takutu Graben in Brazil and Guyana (e.g. Crawford et al. 1985) is controlled by the NE–SW fault system, which extends north along the western margin of the Demerara Plateau. Its synrift fill starts with Upper Triassic–Lower Jurassic strata and ends with Lower–Middle Jurassic evaporites, shale and sandstone.

In the eastern offshore Guyana Basin, it is the Barremian–Albian strata that are understood to represent a synrift fill (e.g. Staatsolie 2009) (Fig. 3). They are truncated by the late Albian erosional unconformity, which has an Aptian–Albian transition age on the Demerara Plateau, and which represents the Equatorial Atlantic break-up unconformity.

Methods

The study relies on 171 reflection seismic profiles provided by CGX Energy Inc. (Fig. 1b) and a three-dimensional (3D) seismic volume, the location of which is kept confidential. Both were tied to 39 wells.

A detailed local interpretation of several seismic sections was made to connect the distal continental margin penetrated by industrial wells with adjacent oceanic crust of the Offshore Guyana Block. The regional interpretation of the entire seismic grid was made extra, resulting in the seismostratigraphic units mapped everywhere. Both sets of horizons are described in Figure 4.

The input for our gravity database came from the National Geophysical Data Center, Earth Gravity Model 2008, satellite-derived marine gravity version DNSC08 and point gravity data over the United States. The data were integrated at the grid level for the entire study area. The Bouguer correction was made with a density of 2670 kg m$^{-3}$ onshore and 2200 kg m$^{-3}$ offshore. The isostatic anomaly was produced using an isostatic correction.
grid produced using the Airy hypothesis. The density contrast used for the Moho discontinuity was 340 kg m\(^{-3}\). All data were levelled relative to Earth Gravity Model 2008 in the WGS84 geographical datum. Two more products of our calculations include the first vertical and total horizontal derivative displays.

The input for our magnetic database came from the NOAA/NGDC Magnetic Crustal Field model, the World Digital Magnetic Anomaly Map, the NGDC EMAG2 map and the North America Magnetic Grid. The data were integrated at the grid level for the entire study area. Data from the first two sources were used to fill the gaps in the EMAG2 database. All data were levelled relative to EMAG2 in the WGS84 geographical datum. Our final result was the total magnetic field map, delivered in the ArcGIS format at a 15 arc-second (c. 500 m) resolution.

Data

The Bouguer gravity image of the oceanic crust is a system of positive anomalies (Fig. 1b). The system of more prominent anomalies of the Accommodation Block is fairly regular, represented by WNW–ESE-striking sub-parallel lows and highs. The Offshore Guyana Block does not have such a system, although some NW–SE-trending, but less prominent, grain is apparent. More and less negative anomalies are associated with thicker and thinner continental crust.

The oceanic crust of the Accommodation Block in the free-air gravity map is a system of distinctive stripe anomalies (Fig. 1a). However, the oceanic crust of the Offshore Guyana Block does not contain any stripe patterns, although it is also associated with negative anomalies. There is an acute angle between the strikes of anomalies in the Accommodation and Offshore Guyana blocks. Those of the Accommodation and Offshore Guyana blocks have WNW–ESE and NW–SE strikes, respectively. The continental crust is imaged by positive anomalies. They are more prominent for the thicker crust of the Guyana Shield and less prominent for the highly stretched crust of the Demerara Plateau. The Guyana margin segment contains two zones of prominent positive anomalies. When located with a help of cross-cutting seismic sections, the first one correlates with a present-day shelf break, occurring right behind the continental–oceanic crust boundary. The second one is associated with the pre-Oligocene shelf break.

The isostatic residual gravity-anomaly map shows that there is a system of isometric negative and positive anomalies (Fig. 5a) between the two elongated positive anomalies of the Guyana margin in the free-air gravity-anomaly map (Fig. 1a).
Fig. 3. Lithostratigraphic chart of the Guyana–Suriname Basin with an indication of horizons interpreted in seismic images (modified from Staatsolie 2009). Regionally interpreted horizons: J, top of Jurassic sediments; BU, upper Aptian–Albian break-up unconformity; S, Santonian unconformity; lE, top of the lower Eocene sediments; lM, lower Miocene base of the main prograding wedge. Other regional horizons; not shown in this chart: CC, top of the continental crust; OC, top of the oceanic crust, ofz, oceanic fracture zone; t, trough; r, ridge. Locally interpreted horizons: LC, top of the Lower Cretaceous Potoco Formation; uA/A, upper Aptian–Albian marker; Cen, top Cenomanian sediments; Tur, top Turonian sediments; NA, the New Amsterdam Formation; O, the Oligocene Pomeroon Formation. SDR, seawards-dipping reflector wedge.

Fig. 4. Profile GE-P-114. Strike-slip fault of the proximal ocean segment terminus active until the Early Eocene in offshore Guyana. See Figure 3 for further explanations. TWT, two-way time.
The total horizontal derivative of the total magnetic intensity map provides the image of oceanic crust lacking the typical stripe anomalies parallel to the mid-oceanic ridge. However, the anomalies, although elongated, are approximately perpendicular to the expected stripe anomalies. Anomalies of the Accommodation and Offshore Guyana blocks have WNW–ESE and NW–SE strikes, respectively. While the former have regionally constant strikes, the latter change their strike from NW–SE to almost NNW–SSE in a direction towards the continental margin.

**Fig. 5.** (a) The isostatic residual gravity-anomaly map with the location of seismic surveys and the oceanic crust–continental crust boundary. Note the rather steep gravity gradients characterizing the Guyana and NE Demerara transform margin segments, while the western Demerara and eastern Demerara extensional margin segments have much shallower gradients. See Figure 1a for further explanations. (b) First vertical derivative of the isostatic residual gravity-anomaly map with the locations of the oceanic crust–continental crust boundary and seismic surveys. White arrows indicate the location of the break-away faults of the gravity-glide system; the thick short white line indicates the orientation of elongated structural highs and lows in the Demerara Plateau. See Figure 1a for further explanations. Note the relationship between the gravity gradients of transform and extensional margin segments similar to that in (a), although less striking.
Both the 111 km high pass and the first vertical derivative of the isostatic residual gravity-anomaly maps provide better detail of the crustal architecture of the Demerara Plateau (Fig. 5b). The ocean–continent transition in the offshore Guyana Basin and along the NE and eastern boundaries of the Demerara Plateau is associated with maximum gradient between the positive anomaly on the continental side and the negative anomaly on the oceanic side. The only area missing such well-developed coupled anomalies exists along the western flank of the Demerara Plateau. This area is imaged by the chaotic system of gravity anomalies, which makes it different from a regular system of elongated anomalies of NNW–SSE strikes in the remaining portion of the Demerara Plateau.

The total horizontal derivative of the isostatic residual gravity-anomaly images the two sets of elongated positive and negative anomalies in the oceanic crust of the Offshore Guyana Block (Fig. 5c). The pattern of individual anomalies is irregular, while it is their zones that keep a regionally consistent trend. The zone trend changes from NW–SE, which is typical of most of the oceanic crust, to almost NNW–SSE near the ocean–continent transition in the east.

The map showing a magnetic-stripe-anomaly-based age of the oceanic crust (Müller et al. 1993) images the boundaries between various oceanic crust terrains, including the Offshore Guyana and Accommodation blocks, the main body of the Central Atlantic, and the Equatorial Atlantic (Fig. 2). It defines the oceanic crust of the Offshore Guyana Block as being of Aptian–Santonian age instead of starting to develop during the Callovian–Oxfordian, which will be documented later in this paper. It also shows that the oceanic crust of the Accommodation Block, with its oldest crust being considerably younger than that of both the Offshore Guyana Block and the main body of the Central Atlantic, belongs to the oceanic crust formed in the region connecting the already spreading Central Atlantic Ocean with the initiating and subsequently developing Equatorial Atlantic Ocean. Figure 2 documents that, being stratigraphically considerably younger, the progressively younger increment zones of the oceanic crust in the Accommodation Block are at the contact with a progressively younger oceanic crust of both the main body of the Central Atlantic and the Offshore Guyana Block. Figure 2 also shows that the spreading vector in the Accommodation Block keeps changing from the ENE–WSW trend characteristic of the initial spreading vector of the Equatorial Atlantic to the WNW–ESE trend characteristic of the spreading vector of the Central Atlantic. Figure 2 documents that this change took place between the late Aptian–Albian and the end-Paleocene.

The first vertical derivative of the isostatic residual gravity shows that the southern boundary of the Accommodation Block meets the Demerara Plateau at its NE corner (Fig. 5b). Then this boundary runs northwestwards in contact with oceanic crust of the Offshore Guyana Block.

The free-air gravity image (Fig. 1a) shows the flow lines parallel to the oceanic fracture zones...
and the stripes of the undeformed oceanic crust between them, which are located in the magnetic-stripe-based age map of oceanic crust (Fig. 2). The flow lines represent the geometry of the spreading vector in the Accommodation Block. While the late Aptian–Albian flow line was at an angle of about 20° to the Central Atlantic vector, the post-Paleocene flow line was roughly parallel to it.

The reflection seismic images of the oceanic crust of the Offshore Guyana and Accommodation blocks (e.g. profile W99-130 in Fig. 6a) show a highly reflective character in its upper portion divided from its sedimentary cover by a strong reflector, and an occasional presence of volcanic mounts. Images of the transition between the oceanic and continental crusts frequently show an undeformed crust on the oceanic side, and a stretched crust deformed by faults and shear zones developed during various time periods before the continental break-up on the continental side. Such difference between images of oceanic and continental crusts is regionally consistent.

Profiles W99-107, W99-109, W99-111 and W99-129 (Fig. 6b) show typical oceanic fracture zones deforming the oceanic crust. They contain ridges and troughs. Troughs of the Offshore Guyana Block were deep isolated basins at least until the Equatorial Atlantic break-up.

Profiles W99-108 and W99-112 (Fig. 6c, d) through the western Demerara margin segment contain features similar to the seawards-dipping reflector (SDR) wedges at the boundary between the continental and oceanic crusts along the western margin of the Demerara Plateau. Their width is small, up to 20 km. They are implied from seismic images only, as no gravity and magnetic forward modelling has been performed, so far. Figure 6c, d documents that these wedges run from the...
continental margin and downlap onto the oceanic crust. They do not thicken towards controlling normal faults in the way in which the synrift fill does in rift units located further landwards (compare the SDR wedge in the centre with the synrift strata in the SE portion of Fig. 6d). They are also more reflective than the synrift fill. No profiles through the Guyana, NE Demerara and eastern Demerara margin segments image SDR wedges.

Profiles such as W99-144 (Fig. 7c) image the Jurassic and Lower Cretaceous Potoco Formation sediments pinching-out landwards against, and lapping onto, the western Demerara margin segment. Such dramatic pinching-out and onlap are missing on the Guyana margin segment (see Fig. 4 for comparison). Here, profiles such as GE-P-114 (Fig. 4) document that a shelf break at the Guyana segment did not undergo any significant oceanwards shift during the Cretaceous–Early Eocene.

Based on the seismically imaged youngest sediments being deformed by a respective fault set and the oldest sediments being undeformed by this set,
the following faulting events are observed in the region:

- Late Triassic–Late Jurassic normal faulting (Fig. 8a);
- late Barremian–late Aptian/Albian faulting (Fig. 8b);
- late Aptian/Albian–early Eocene faulting (Fig. 8c);
- Callovian/Oxfordian–late Aptian/Albian faulting related to gravity gliding on the western flank of the Demerara Plateau (Figs 6a, c, d & 7a);
- faulting related to the Middle Miocene gravity gliding (Fig. 4);
- faulting related to the present-day gravity gliding (Fig. 4).

**Interpretation**

*The Guyana–Suriname–French Guiana continental margin*

The offshore reflection seismic images tied to wells reveal that this margin can be divided into the Central and Equatorial Atlantic margins. The former contains the Guyana and Western Demerara.
Fig. 6. (Continued) (d) Profile W99-112 showing the image of the SDR wedge-looking feature in the transition region between the oceanic and continental crusts along the western extensional margin of the Demerara Plateau. See Figure 3 for further explanations. Note the extensional faults of gravity glides truncated by the upper Aptian–Albian break-up unconformity associated with the opening of the Equatorial Atlantic. They are missing in the younger strata. TWT, two-way time.
Fig. 7. (a) Profile W99-108 documenting a well tie from the Demerara Plateau with deep penetration allowing the Upper Jurassic sediments to be traced all the way down to the lowermost sedimentary cover of the oceanic crust of the Offshore Guyana Block. See Figure 3 for further explanations. Note the extensional faults of gravity glides truncated by the upper Aptian–Albian break-up unconformity associated with the opening of the Equatorial Atlantic. They are missing in the younger strata. The NW side of the section images synrift normal faults deforming only the Jurassic portion of the sedimentary cover.
segments. The latter consists of the NE Demerara and eastern Demerara segments.

Starting with Central Atlantic, the western Demerara segment is interpreted as an extensional margin. The reasons for this interpretation are as follows. Its gravity and reflection seismic images indicate a distinct crustal thinning zone between the normal continental crust and the break-up trajectory (Figs 5a, b, 6c & 7a). It can be implied from a shallower-dipping gravity gradient, such as that in the isostatic residual gravity-anomaly map (Fig. 5a). Its upper-crustal portion is accommodated mostly by oceanwards-dipping normal faults, imaged in reflection seismic data (Fig. 7a). Similar Central Atlantic rift faults are located in the west and centre of the Guyana margin segment, landwards from the transform fault zone (Fig. 8a). Not having deep enough seismic images, we assume that these faults detach at the brittle upper crust–ductile lower crust transition and that the lower crust was thinned by ductile deformation mechanisms.

When restored to their pre-Equatorial Atlantic break-up location, the western Demerara Plateau normal faults become parallel and neighbours to the ones of the western Guinea Plateau (see the Guinea Plateau fault map and profiles in Marinho et al. 1988), which are also mostly oceanwards-dipping. Most of Guinea faults have their upper propagation tips located inside the Jurassic strata, although some penetrated just a little into the Lower Cretaceous section. Seismic images of the western Demerara segment (Figs 6c, d & 7a) indicate roughly similar fault activity timing. While the Late Triassic–Late Jurassic activity can be related to the Central Atlantic rifting, the Early Cretaceous reactivation must be due to the uplift of both the Demerara and Guinea plateaus after the Equatorial Atlantic break-up.

The western Demerara extensional margin can be associated with implied SDR wedges (Fig. 6c & d), which are described in the ‘Data’ section of this paper. They are assumed to represent basaltic volcanic products intercalated with sediments during break-up. These wedges are located in the Jurassic section. Their presence would indicate a magma-rich character of this margin, making it similar to the Central Atlantic margins from which it drifted away, being separated by the growing Equatorial Atlantic, after late Aptian–Albian time. Magma-rich segments of the Central Atlantic break-up trajectory include the Baltimore Canyon

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**Fig. 7. (Continued)** (b) Profile W99-150 documenting a well tie from the Demerara Plateau with deep penetration allowing the Upper Jurassic sediments to be looped all the way down to the lowermost cover of the oceanic crust of the Offshore Guyana Block. See Figure 3 for further explanations.
Trough, the Carolina Trough, the Georges Bank and the southern two-thirds of Nova Scotia (Benson & Doyle 1988; Schlee & Klitgord 1988; Austin et al. 1990; Sheridan et al. 1993; Keen & Potter 1995; Oh et al. 1995; Talwani & Abreu 2000; Dehler 2010; Deptuck 2011; Dehler & Welford 2013). Further north, the trajectory gains a magma-poor character (Dehler 2010; Dehler & Welford 2013). In the case of the African conjugates, the presence of the SDR wedges is still in dispute (e.g. Davison 2005; Labails 2007; Klingelhofer et al. 2009; Labails et al. 2009), and clear evidence is missing either due to geological or imaging reasons. The correlation between the magma-rich western Demerara segment and the magma-rich margins of the main body of the Central Atlantic, if proven, would provide an important marker for the plate reconstructions because neither the adjacent Equatorial Atlantic margins nor the Guyana margin segment have magma-rich characteristics.

The continental break-up timing along the western Demerara segment is difficult to determine. The magnetic-stripe-anomaly record in the Offshore Guyana Block is not apparent. The observed anomalies are, instead, controlled by its deformation grain (see the ridges and troughs apparent in Fig. 5c, and the more-or-less WNW–ESE grain of anomalies in Figs 1a, b & 5a, b). Therefore, it is practically impossible to interpret the age of its crust based on stripe anomalies.

However, there are other ways of defining this age. The first, and most important, one is the interpretation of seismic images tied to wells. The seismic profiles through the boundary between the

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**Fig. 7. (Continued) (c) Profile W99-144 through the western extensional margin of the Demerara Plateau showing the Jurassic and Potoco Formation sediments pinching out and onlapping landwards. See Figure 3 for further explanations. TWT, two-way time.**
Offshore Guyana Block and the Guyana and western Demerara continental margin segments, which are tied to stratigraphic data of the continental margin wells, allow one to see that the oldest sedimentary cover of the oceanic crust near the western Demerara extensional margin segment dates to the Callovian–Oxfordian (Fig. 7a, b). In comparison to the map of the oceanic crustal age (Müller et al. 2008) (Fig. 2), this fact documents that the oldest oceanic crust of the Offshore Guyana Block is either minimally coeval with that of the main body of the Central Atlantic to the north of it, if we took the magnetic-stripe-anomaly-based age of 158 Ma (Oxfordian) from Müller et al. (2008), or younger if we took stratigraphic constraints on the break-up unconformity from the regions further north that suggest the Hettangian–Aalenian (Tankard et al. 1989; Welsink et al. 1989; Wade & MacLean 1990; Aajdour et al. 1999; Davison et al. 2002; Echarfaoui et al. 2002). Regardless of being less precise, this age determination allows one to see that the continental break-up along the western Demerara segment took place coevally or a little later than that of the southern portion of the main body of the Central Atlantic to the north of it.

The second way is the interpretation of gravity maps tied to interpreted seismic sections. Knowing the NW–SE to NNW–SSE trends of the oceanic fracture zones in the Offshore Guyana Block, which are interpreted from the total horizontal derivative of the isostatic residual anomaly map (Fig. 5c) and the cross-cutting reflection seismic images (Fig. 6b), allows one to conclude that its oldest oceanic crust is in the NE–SW-trending stripe right next to the western Demerara extensional margin segment.

The third one is to use our determined structural architecture, place it into the GPlates reconstruction software (GPlates 2015) and restore it into its position prior to the opening of the Equatorial Atlantic, Restoring the Demerara Plateau together with the adjacent Offshore Guyana Block to their pre-late Aptian–Albian location to the south of the Guinea Plateau, together with the adjacent main body of the Central Atlantic, using the translation and rotation constraints from Seton et al. (2012), allows one to interpret the continental break-up along the western Demerara extensional margin segment as taking place around the Middle–Late Jurassic.

One more indication of the western Demerara margin segment being extensional is the evidence of its significant post-break-up isostatic uplift, which is typical of extensional margins (see van Balen et al. 1995; van der Beek et al. 1995; Burov & Cloetingh 1997). The evidence for uplift is either a distinct pinch-out of the post-Central Atlantic break-up to pre-Equatorial Atlantic break-up strata against the western Demerara extensional margin segment or its onlap onto it (Fig. 7b, c). Another piece of evidence is a system of Jurassic–Early Cretaceous gravity glides, which are older than the Equatorial Atlantic break-up unconformity of late Aptian–Albian age, that occupy only a single location in the study area – the western flank of the Demerara Plateau (Figs 6c, d & 7a). The flank must have achieved its gravitational instability by an asymmetric uplift, being maximal near the break-up trajectory and progressively smaller landwards, which is typical for post-break-up extensional margin histories.

The gravity-gliding region is outlined in Figure 5b. It is divided from the rest of the Demerara Plateau by the arcuate trace of its break-away fault zone. Seismic profiles (Figs 6a, c, d & 7a) image listric normal faults developed in the extensional domain of this gravity-glide system. The arcuate break-away fault-zone trace projects to different seismic profiles differently. Some image break-away faults above the oceanic–continental transition (Fig. 6a), other image break-away faults further landwards (Figs 6c, d & 7a). Contractional and translational domains of the gravity-glide system are located on top of the oceanic crust, while the extensional domain may or may not reach it. Interpreted images indicate that the gravity-glide system is detached inside the Jurassic–Lower Cretaceous strata, which are known from the literature to contain evaporites (Crawford et al. 1985; Davison et al. 2002). The presence of evaporites in the detachment horizon can also be implied from the reflection seismic images containing various salt-roller- (Fig. 6d) and salt-pillow-looking features, although further verification by forward gravity modelling would be needed to test the reasonability of this interpretation. The long-lasting activity of gravity glides during the more-or-less entire Callovian/Oxfordian–late Aptian/Albian time interval can be inferred from the thickening of the syntectonic sediments of different stratigraphic levels towards normal faults (Fig. 6a).

The Guyana margin segment is interpreted as a transform margin. The reasons for this interpretation are the following. Its gravity images indicate a lack of wide thinning zone between the normal continental crust and the break-up trajectory (Figs 1b, 4, 5a, b & 8c). However, rather abrupt thinning can be implied. The upper-crustal portion is deformed predominantly by strike-slip faults (Figs 4 & 8c). A lack of both distinct pinch-outs and onlaps in the post-break-up strata and a lack of the Callovian/Oxfordian–late Aptian/Albian gravity-glide systems along this margin (Figs 4 & 8c) indicates its subdued isostatic uplift after the break-up, which is typical of transform margins. It is typical owing to the fact that a fast juxtaposition of warm
oceanic crust and continental crust results in high
temperatures and strongly weakened lithosphere.
As a result, the transform margin gains very low
flexural rigidity, close to that of local Airy isostasy,
and flexural and rebound effects are unlikely to play
a major role (Karner & Watts 1982; Holt & Stern

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Fig. 8. (a) Profile 93MGH-S4 documenting the Late Jurassic normal faulting in the Guyana transform margin segment. See Figure 3 for further explanations. (b) 3D seismic volume in the Guyana transform margin segment showing the late Barremian–late Aptian/Albian strike-slip faulting and pull-apart development.
A missing distinct uplift of the Guyana transform margin segment is further indicated by a lack of any important erosional event at this margin, which would supply the sediment into the adjacent oceanic basin. A lack of such supply is documented by the shelf break remaining at the same location after the Callovian–Oxfordian continental break-up until the early Eocene (see Figs 4 & 8c).

Three-dimensional seismic data indicate the existence of a rather dense system of strike-slip faults, roughly parallel to the break-up trajectory (Fig. 8b). Although the strike-slip fault imaging is less clear, overlapping the seismic section with the 3D seismic volume allowed us to define them in seismic sections and to follow them in the rest of the 2D grid. They are imaged here as subvertical zones of reflector truncations, usually lacking flower structures (Figs 4 & 8c).

Numerous interpreted strike-slip fault zones terminate in close proximity to the Demerara Plateau, where their displacements were dissipated inside the horsetail structures (Fig. 8b). Figure 8b shows that some strike-slip fault zones never reached

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**Fig. 8. (Continued)** (c) Profile GE-P-67 through the Guyana transform margin segment imaging a strike-slip fault active until the Early Eocene. See Figure 3 for further explanations.
development stages more mature than the initial stages characterized by the en echelon arrangement of the Riedel shears, while others underwent development of all fault-zone-building types of shears and their full linkage. This system of strike-slip faults, which failed to reach the break-up, was sinistral. Inside their horsetail structures, the WNW–ESE-striking strike-slip faults progressively changed to NE–SW-striking sinistral oblique-slip faults and eventually to NNE–SSW-striking normal faults. All strike-slip faults of this system must have formed an efficient stress-releasing accommodation zone that prevented the Central Atlantic from southwards propagation towards the failed Takutu Graben. The fact that this accommodation zone in offshore Guyana was sinistral, instead of dextral, indicates that the initial Central Atlantic spreading centres parallel to the western Demerara extensional margin segment were clearing the Guyana transform margin segment laterally and towards the NW. A sinistral sense of displacement is in accordance with the sense that is required for the transform to link the southern terminus of the Central Atlantic with the northern terminus of the Bajocian/Oxfordian–Tithonian/Valanginian oceanic corridor in the Gulf of Mexico (see Buffler & Sawyer 1983; Ross & Scotese 1988; Pindell & Kennan 2009; Seton et al. 2012 for the age of active spreading) and the subsequent Early Cretaceous oceanic corridor in the proto-Caribbean region.
(see Ross & Scotese 1988 and Seton et al. 2012 for a rough estimate of the reconstructed synthetic ocean). It is also similar to the sense of the western Florida transfer faults (Dobson & Buffler 1997; Denman & Adamick 2000).

Along the Central Atlantic trend, this strike-slip fault system divided the rift zones of the main body of the Central Atlantic, which reached continental break-up, from the southern rift zones, which failed (Fig. 9b). The portion of the system in the study area must have eventually been reactivated as dextral either some time during the late Barremian–late Aptian/Albian dextral shearing along the future Equatorial Atlantic break-up trajectory or during the subsequent late Aptian/Albian–Paleocene Equatorial Atlantic spreading. We do not have the data to determine this timing, lacking the fault/fracture data from outcrops and only having seismic images that are not suited to the determination of the displacement vector. However, as we believe that the NNE–SSW-striking normal faulting in the horsetail structures at the eastern end of the Guyana transform margin segment would change to reverse faulting if the system was reactivated as dextral enables us to rule out the pre-late Aptian–Albian period. Our 3D seismic data indicate that only a few straight and NW–SE-striking strike-slip faults remained active for different portions of the late Aptian/Albian–early Eocene time period. Having no displacement markers for this time period, we are left with plate reconstructions (e.g. Scotese 1998; Golonka 2000; Seton et al. 2012) that imply dextral displacements. Two-dimensional seismic data reveal that a large number of strike-slip faults stopped functioning at the time of the Equatorial Atlantic break-up, including all those located in the distal margin (Fig. 4). Small groups in the proximal margin were active until the Cenomanian–Turonian, others until the end-Maastrichtian and a few were active up to the early Eocene (Figs 4 & 8c). The longer-lasting faults must have been needed for the accommodation of differential movements between fault blocks during the time interval required for the Equatorial Atlantic and the Central Atlantic to reach parallel seafloor spreading. The progressively decreasing number of active strike-slip faults during this late Aptian/Albian–early Eocene time interval may have been related to the original fault geometries leaving the location of favourable geometries with respect to the governing stress field as a result of the progressive clockwise rotation of the Guyana transform margin segment, which is obvious when one closes the space between the main body of the Central Atlantic and the offshore Guyana Block–South America, which is occupied by the Accommodation Block and the Equatorial Atlantic in Figure 9a, to reach the plate situation shown in Figure 9b.

While the eastern portion of the Guyana transform margin segment contains mostly strike-slip faults and horsetail structures with dozens of small pull-apart basins, some NNE–SSW-trending failed rift units of the Central Atlantic rift system are imaged by seismic profiles in the western portion (Fig. 8a). Their Jurassic activity can be interpreted from the synrift strata thickening towards the controlling normal faults (Fig. 8a). The structural remnants of these rift units are relatively rare. Some occur in the central portion of the Guyana transform margin segment, indicated by a combination of seismic data and negative anomalies of the isostatic residual gravity-anomaly data (Fig. 5a).

The NE Demerara segment is interpreted as the transform margin. This is based on implications from gravity data (Fig. 5a, b) and interpretation of seismic images, which do not indicate any wider zone of progressive crustal thinning towards the break-up trajectory. Not having the seismic coverage comparable to that of the Guyana transform margin segment to interpret the entire dextral strike-slip fault system leading to the late Aptian–Albian break-up, we have only a small number of strike-slip faults of this system imaged in a few profiles. Figure 9a, b shows that the NE Demerara transform margin segment can be placed right next to the SW Guinea Plateau transform margin segment, the fault system of which consists of a system of WNW–ESE-striking steeply dipping faults in the central portion of this segment with horsetail structures at both its ends, where strike-slip faults turn into NW–SE-striking dextral oblique-slip faults and eventually into NWW–SSE-striking normal faults (Marinho et al. 1988). The system is about 50 km wide. In addition, the plate reconstruction of the opening of the Equatorial Atlantic, made together with the ends of the southern Central Atlantic and the northern South Atlantic by Nemčok et al. (2013), requires a dextral strike-slip upper-crustal break-up along the NE Demerara transform margin segment. The literature documents that this fault system was active during late Barremian–late Aptian (e.g. de Azevedo 1991; de Matos 2000).

The eastern Demerara margin segment is interpreted as an extensional margin. Its extensional break-up is required by the plate reconstruction carried out by Nemčok et al. (2013), and data on the structural architecture presented by Sapin et al. (this volume, in review) are in accordance with this interpretation. A structural grain represented by NW–SE-striking structural highs and lows parallel to the break-up trajectory is indicated by the gravity data (Figs 1b & 5b, c). Seismic sections across this grain image a system of half-graben-like features separated by symmetric basement highs and rotated footwall edges (Fig. 8d). Some of the synrift strata underwent episodes of transpressional
folding (Fig. 8d), which is typical of pull-apart terrains where far-travelled blocks are under varying stress regimes depending on their location with respect to the complex geometries of the controlling strike-slip fault zones that consist of straight segments, overstep zones and bends.

A limited number of seismic profiles and the isostatic residual gravity-anomaly map (Fig. 5a), together with its derivatives (Fig. 5b, c), allow the system of pull-apart basins in this margin segment to be interpreted as it developed in the large overstep region between the two NW–SE-striking dextral strike-slip fault zones. The NW fault zone forms the NE Demerara transform margin, while the SE fault zone connected the SE Demerara Plateau with the NW Monrovia Basin prior to continental break-up.

Both aforementioned Equatorial Atlantic margin segments, together with the Demerara Plateau, recorded isostatic uplift after the Equatorial Atlantic break-up event. Albian strata penetrated by the Demerara Plateau wells indicate that the depositional environments reacted to the uplift by changing into shallow-water and sub-aerial settings. Being asymmetric, this uplift affected the eastern Demerara Plateau the most. This must have evened up the opposite Demerara tilt remaining after the Central Atlantic break-up, because this was the time when the Callovian/Oxfordian–late Aptian/Albian gravity gliding on the western flank of the Demerara Plateau terminated (see Figs 6a, c, d & 7a). The areal extent of this uplift, affecting mostly the Demerara Plateau, was not areally extensive enough to affect the Guyana transform margin segment significantly (cf. Figs 4 & 8a, c, showing profiles through the Guyana transform margin segment, with Fig. 8d, showing the section through the Demerara Plateau).

The Offshore Guyana Block

The Offshore Guyana Block is formed by the oceanic crust bounded by the Guyana transform margin segment in the SW, the Demerara Plateau in the SE, the Caribbean Plate in the NW and the Accommodation Block in the NE. Its magnetic image lacks magnetic-stripe anomalies. However, both gravity and magnetic data document anomalies elongated in a NW–SE direction, especially the total horizontal derivative of the isostatic

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Fig. 9. (a) Map of the Accommodation Block with time constraints on its late Aptian/Albian–Paleocene growth and deformation. 1, onshore continental crust; 2, offshore continental crust; 3, Jurassic oceanic crust; 4, Caribbean Plate; 5, oceanic crust of the Accommodation Block; 6, oceanic fracture zones of the Accommodation Block; 7, isochrones of oceanic crust age; 8, well; 9, trace of the reflection seismic profile; 10, Jurassic isochrones of oceanic crust age interpreted in this paper; 11, boundary between the Accommodation Block and the Central Atlantic crust for the crust formed by divergent spreading in these two terrains; ES, WS; eastern and western segments of the Accommodation Block.
residual gravity-anomaly map (Fig. 5c). The anomalies image a system of NW–SE-trending troughs and ridges associated with oceanic fracture zones, which can be seen in seismic profiles such as that shown in Figure 6b, and stripes of the oceanic crust among the oceanic fracture zones. Such a magnetic and gravity indication of the highly deformed character of the oceanic crust of the Offshore Guyana Block, which disrupts typical gravity and magnetic records of the oceanic crust, is in striking contrast with the typical magnetic image of the oceanic crust of the main body of the Central Atlantic characterized by mid-oceanic ridge-parallel magnetic-stripe anomalies and typical gravity images containing flow lines perpendicular to magnetic-stripe anomalies.

The observed ridges and troughs are about 15–50 and 10–25 km wide, respectively. Their spacing is about 150 km. Ridge elevations and depths of troughs are similar, reaching about 1 s two-way time (TWT) in the time-migrated reflection seismic images. The ridges have symmetrical profiles (Fig. 6b). They are deformed by a system of faults with a distinct dip-slip displacement. These faults are roughly parallel to the trend of oceanic fracture zones and dip down the slope on both sides of the

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**Fig. 9. (Continued)** (b) Plate reconstruction of the study area for 140 Ma performed using GPlates reconstruction software (GPlates 2015), and translation and rotation constraints shown in Seton et al. (2012). 1, onshore continental crust; 2, oceanic crust; 3, offshore continental crust; 4, seafloor spreading ridge; 5, failed portion of the Central Atlantic Rift System located in the study area (FRS); 6, oceanic fracture zone; 7, isochrones of oceanic crust age. A_CC, African continental crust; SA_CC, South American continental crust; OC, Central Atlantic oceanic crust. GP and DP are the future Guinea and Demerara plateaus, which are not yet separated from each other. Note that the figure only shows a small portion of the transform fault system that once linked the southern terminus of the Central Atlantic with the northern terminus of the oceanic corridors in the Gulf of Mexico, and is most probably linking the Central Atlantic with the northern terminus of the proto-Caribbean region oceanic corridor during the time of this reconstruction.
ridge summit. They do not cut very deep and die out without being detached. Based on their sense of dip symmetry around the summit and a lack of detachment, we interpret them as having been controlled by the release of the flexural stresses accumulated by the ridge uplift. Conversely to ridges, the troughs are asymmetrical, represented by half-graben in profiles (Fig. 6b). Similar to inferences made from the gravity-anomaly patterns (e.g. Fig. 5c), the seismic-reflection-based contour maps of the oldest strata tops show that the system of ridges and troughs comprising the oceanic fracture zones is somewhat irregular and wide. This ridge–trough system is different from the oceanic fracture zones traditionally interpreted as discrete planar faults. Here, it is the overall oceanic fracture zone trend that keeps a regular geometry and not its individual ridges and troughs. The overall width of the fracture zones ranges from 50 to 100 km.

The cross-cutting relationship of both the flexure-driven and trough-controlling faults with sedimentary cover and the age of sediments syntectonic to these faults indicate that the end of their activity occurred at around the time of the development of the Equatorial Atlantic break-up unconformity. Apart from the oldest segments of the oceanic fracture zones, which trend approximately NNW–SSE, the NW–SE-trending remaining portions of the oceanic fracture zones (Fig. 5c) are roughly parallel to the system of strike-slip faults of the Guyana transform margin segment (Fig. 8b, c). We conclude that both of these comprise a broad strike-slip faulting corridor to the south of the Accommodation Block that was needed to accommodate the east–west-trending spreading of the Central Atlantic and the NE–SW-trending $\alpha_2$ of the stress regime controlling the development of the strike-slip fault zones and the pull-apart systems that led to the opening of the Equatorial Atlantic.

Figure 9a, b shows that when the NE boundary of the Demerara Plateau is juxtaposed to the SW boundary of the Guinea Plateau (see also Scotese 1998; Golonka 2000; Schettino & Turco 2009; Yang & Escalona 2011; Basile et al. 2012; Nemčok et al. 2013), removing the post-late Aptian–Albian crust of the Central Atlantic and the entire crust of both the Equatorial Atlantic and the Accommodation Block, the oceanic fracture zones of the Offshore Guyana Block and those of the main body of the Central Atlantic become parallel. During this process, the Offshore Guyana Block has to undergo a sinistral rotation of about 20°. This indicates its dextral rotation between the late Aptian–Albian and the end-Paleocene, during the spreading in the Accommodation Block and the Equatorial Atlantic, both trying to reach parallelism with the spreading of the Central Atlantic. The Offshore Guyana Block underwent this rotation together with South America to which it must have been attached without any distinct differential movements, because its faulting events at the oceanic fracture zones terminated prior to its dextral rotation. The space between the rotating Offshore Guyana Block–South America system and main body of the Central Atlantic was filled by the progressively accreting oceanic crust of the Accommodation Block, which is described in the following subsection.

The Accommodation Block

The Accommodation Block is a special block of oceanic crust because its neighbours are oceanic terrains only, apart from two exceptions: where the eastern and western ends of its southern boundary touch the Guinea and Demerara plateaus, respectively (Figs 1a & 9a). The Accommodation Block started to form when the opening of the Equatorial Atlantic – which completed the separation of Africa from South America, propagating from east to west, and connecting the South and Central Atlantic oceans – had to penetrate about 1000 km of the Central Atlantic oceanic crust in order to develop a new triple junction. The junction formed when the propagating Equatorial Atlantic met the spreading ridge of the Central Atlantic.

However, when the Equatorial Atlantic seafloor spreading started some time during the late Aptian–Albian, with its break-up trajectory between the future Demerara and Guinea plateaus (Fig. 9a), a major problem emerged. While the initial late Aptian–Albian spreading vector of the Equatorial Atlantic had a NE–SW trend, the coeval Central Atlantic vector had an east–west trend. The spreading vectors of both oceans in their contact zone became parallel only during the Paleocene, as can be seen from the flow lines in the free-air gravity map (Fig. 1a) and the map of the age of the oceanic crust (Fig. 2). The late Aptian/Albian–Paleocene time period required for reaching this parallelism is exactly the time when progressively newer and newer east–west-trending stripes of the oceanic crust kept being added to the northern side of the already existing stripes of the Accommodation Block (Figs 1a & 9a) that predominantly grew up by the oceanic crust accretion along the north–south-trending spreading ridge system. Therefore, the Accommodation Block recorded both east–west divergence between North America and NW Africa, and north–south divergence between North America and South America–Offshore Guyana Block. Because the latter was subordinate to the former, the triangular ends of the Accommodation Block with late Aptian/Albian–Paleocene crust are very squat (Fig. 9a). Because of the subordinate growth of the Accommodation Block in the northern direction, progressively newer and newer stripes
of the Accommodation Block were ‘filling the space’ between the southernmost seafloor-spreading centre of the main body of the Central Atlantic and the northwesternmost spreading centre of the Equatorial Atlantic moving away from each other because of their diverging spreading pattern.

Because of the northwards growth of the Accommodation Block, its contact with the main body of the Central Atlantic is marked by truncations of its flow lines in the free-air gravity and crustal age maps (Figs 1a & 2) against the southern boundary of the main body of the Central Atlantic, which is parallel to the flow lines to the north of it. The southernmost flow line of the Accommodation Block, which started to form during the early Alban (110 Ma), is truncated against the Oxfordian (158 Ma) crust of the main body of the Central Atlantic (Fig. 9a). The northernmost flow line, which started to form during the Cretaceous–Palaeogene boundary (65 Ma), is truncated against the slightly older Cretaceous–Palaeogene crust of the main body of the Central Atlantic (Fig. 9a). The remaining flow lines of the Accommodation Block located between these two flow lines have an age gap between their initial crust and the adjacent Central Atlantic crust that is progressively smaller from the SE to the NW along the contact with the main body of the Central Atlantic (Fig. 9a).

A mirror image of this situation occurs along the western end of the Accommodation Block, although the truncations in the free-air gravity map are not as distinct as those at its eastern end owing to the flow lines indicated by the more and less pronounced negative anomalies, which makes their definition less obvious (Fig. 1a). The gravity image here is affected by the thick sedimentary wedge formed in front of the Caribbean Plate overriding the main body of the Central Atlantic, the Accommodation Block and the Offshore Guyana Block. One more reason for the thick sedimentary wedge causing the shift of gravity anomalies in the free-air gravity map towards negative values is the sediment load brought by the Orinoco and Amazon rivers. Where the oceanic crust is far enough to the east from the influence of these sources of thick sedimentary cover (Fig. 1a), its flow lines become indicated by positive ridges and mounts, and middle-range to negative troughs and depressions. The only exception is the Offshore Guyana Block, the gravity image of which is affected by these sediments.

The main body of the Central Atlantic

Oceanic crust of the main body of the Central Atlantic contains flow lines (Figs 1a & 2) that reveal the spreading vector geometry for its entire development history. Since the onset of spreading, regional extension has been roughly constant apart from a single exception of a pronounced change from WNW–ESE to ENE–WSW from 65 to 55 Ma (from the Cretaceous–Palaeocene boundary up until the boundary of the Thanetian–Ypresian). This period overlaps with the time (65 Ma) when the northwards growth of the Accommodation Block stopped, and the Equatorial Atlantic and Central Atlantic spreading vectors became parallel (cf. Figs 1a, 2 & 9a).

While the Central Atlantic flow lines comprise a relatively parallel system, their pattern is deformed in the narrow zone to the north of the Accommodation Block (Fig. 1a), in the upper Aptian/Albian–Palaeogene crust. Here the pattern is rather contorted, and is characterized by areas with flow-line bifurcations and flow-line segment shingling. We interpret this deformation as a response to the interaction between the Accommodation Block and the main body of the Central Atlantic. It has developed on top of the role taken by the Accommodation Block during the time when the Central and Equatorial Atlantic oceans were ‘sorting out’ the kinematic imbalance at their contact.

The Equatorial Atlantic

Oceanic crust of the Equatorial Atlantic contains relatively apparent flow lines (Figs 1a & 2) indicating the history of its interaction with the crust of the Accommodation Block. The boundary between these two crusts does not contain any system of flow-line truncations on the side of the Accommodation Block, which makes it different from the boundary between the main body of the Central Atlantic and the Accommodation Block. A small exception from this rule is a narrow stripe of crust with an age of 65–55 Ma (from the boundary of the Cretaceous–Palaeocene up until the Thanetian–Ypresian) in the Accommodation Block that underwent the episode of ENE–WSW spreading and which contains truncations. Interestingly, while both the Central Atlantic and Accommodation Block recorded this short-lived ENE–WSW spreading event, the adjacent Equatorial Atlantic crust did not. It can serve as a record of the last jostling between the Central and Equatorial Atlantic oceans before their spreading reached parallelism and the role of the Accommodation Block was terminated.

Discussion

The development history of the southern terminus of the Central Atlantic segment of the Atlantic must have been influenced by the developing history of the neighbouring oceans, which will be discussed before we focus on this terminus.
Opening history of the northernmost South Atlantic

There is evidence of the pre-existing fault zones producing the rifting in the northernmost portion of the South Atlantic rift system complex (e.g. Jardim de Sá 1984; de Matos 1987; Chang et al. 1988). These zones were part of the Brazilian-Pan-African terrains reworked by the Proterozoic orogeny.

The initial rifting here started during the Late Jurassic (Chang et al. 1988). It did not make it through the Pernambuco–Ngaoundere and Patos fault zones on its way north. This is indicated by the presence of the Upper Jurassic sediments in the Jatobá–Tucano–Recôncavo, Sergipe–Alagoas and Araripe basins to the south, and their absence in the Rio de Peixe and Potiguar basins to the north of the Patos Fault Zone.

The Neocomian–early Barremian main rift phase did not succeed in propagating through the aforementioned fault zones either (Chang et al. 1988), although the extensional deformation formed a number of intra-cratonic basins along the Cariri–onshore Potiguar trend trying to bypass the problem with propagating through the pre-existing fault zones, which kept using the stresses accumulated for the northwards rift propagation for their reactivation. The northern South Atlantic terminus, thus, behaved as a complex accommodation zone, balancing extensional deformation in the Jatobá–Tucano–Recôncavo and Sergipe–Alagoas rift zones with coeval extension in the intra-cratonic rift branch of the Cariri–Potiguar trend.

The late Barremian rifting represented the final rifting stages of rift units to the south of the Pernambuco–Ngaoundere and Patos fault zones, and the rift initiation in the eastern Equatorial Atlantic domain (Chang et al. 1988; Popoff 1988; Benkhelil et al. 1988). The regional extension changed from NW–SE striking to WNW–ESE striking, and rifting in the Cariri Valley and onshore Potiguar basins was aborted. Pre-existing NE–SW-striking normal faults of the Potiguar Basin were reactivated as sinistral transtensional strike-slip faults, and new graben opened to the west of the Potiguar Basin.

The rift system propagated northwards through the Pernambuco–Ngaoundere Fault Zone during the Aptian, as documented by the synrift fill of half-graben in the Pernambuco–Paraíba Basin (de Matos 1987; Gomes et al. 2000; Nemčok et al. 2004), while the dextral strike-slip linkage of the Potiguar Basin with the Benue Trough controlled the northern terminus for a little longer (de Matos et al. 1987). The northwards propagation of both the NE–SW-trending Sergipe–Alagoas sinistral strike-slip and the roughly north–south-trending normal fault systems during the Aptian–Albian transition made it through this last continental bridge (Rosendahl et al. 2005).

One last important fact about the South Atlantic is its opening rate. This can be calculated from its length (3560 km) and the ages of the initial oceanic crust (130–135 and 115–120 Ma) at its ends, taken from Müller et al. (1993, 1997, 2008), and which yields a rate of 0.24 m a⁻¹. For comparison, the Central Atlantic rate can be calculated from its length (3480 km) and the Hettangian and Callovian ages of the oceanic crust at its ends, giving a rate of 0.08 m a⁻¹.

Opening history of the Equatorial Atlantic

The onset of the basin formation along the intracontinental strike-slip zones in the Equatorial Atlantic region has a late Barremian age (e.g. Popoff 1988; de Matos 1992; Guiraud & Maurin 1992), based on the age of the basal transgressive sediments in the Benue Trough, and the ages of the later synrift sediments on the Brazilian continent and in the Ivory Coast coastal area. This took place while the South Atlantic was waiting with breaching through the dextral strike-slip linkage of the Potiguar Basin with the Benue Trough.

The general westwards propagation of the Equatorial Atlantic rifting can be demonstrated as being based on younging basal sediments in developing basins. The Potiguar Basin records the Aptian sediments resting on the Neocomian sediments transgressively (de Azevedo 1991). The oldest sediments of the Mundau Basin have an early Aptian age (Costa et al. 1990). The Gurupi graben system, and the Barreirinhas and Para Maranhão basins, document roughly an Aptian age for basal sediments (Cainelli et al. 1986; de Azevedo 1991). The Marajo and Foz do Amazonas basins have their basal sediments dating to the Aptian–Albian boundary and the upper Aptian–Albian, respectively (de Azevedo 1991). When we take the oceanic crust age constraints from Müller et al. (1993, 1997, 2008), we find out that it took about 5 Ma for the 3090 km-long Equatorial Atlantic to propagate, giving us a rate of 0.62 m a⁻¹. This rate is 0.38 and 0.54 m a⁻¹ faster than the rates of the South and Central Atlantic oceans, respectively; making the rates for the South and Central Atlantic similar to each other, and that of the Equatorial Atlantic different to them both, being much faster.

Linkage of the South and Central Atlantic oceans by the Equatorial Atlantic

This discussion and our research indicate that the Central and Southern Atlantic oceans had their southern and northern terminuses, respectively,
controlled by their inability to propagate through a system of strike-slip faults during the period from the Callovian–Oxfordian to the late Barremian. It took the South Atlantic up until the Aptian to breach through a wide system of roughly perpendicular dextral strike-slip fault zones and related faults, almost going for a ‘breaching one at the time’ mechanism. The southern terminus of the Central Atlantic was kinematically linked via a large system of roughly perpendicular sinistral strike-slip fault zones and related faults, with the oceanic tracts in the Gulf of Mexico and proto-Caribbean regions both being offset an enormous distance to the NW of the Central Atlantic trend. The linkage with the Gulf of Mexico was active during its oceanic spreading that started some time during the Bajocian–Oxfordian and stopped at some point during the Tithonian–Valanginian (e.g. Buffler & Sawyer 1983; Ross & Scotese 1988; Pindell & Kennan 2009) because of the ridge jump into the proto-Caribbean region (e.g. Ross & Scotese 1988; Seton et al. 2012). As indicated by plate reconstructions, the linkage with the proto-Caribbean region was most probably of subsequent Early Cretaceous age (Ross & Scotese 1988; Seton et al. 2012). Its deformation record must have been consumed by subduction at some points between its start and the end of the Cretaceous, as indicated by plate reconstructions (see Seton et al. 2012 and references therein). The described strike-slip fault system was never breached in the study area, leaving the rift units in the study area to the south of it failing to reach the continental break-up (Fig. 9b).

From the late Barremian up until the Aptian–Albian transition, southern and northern termini of the Central and South Atlantic oceans, respectively, were linked by the dextral system of strike-slip fault zones and pull-apart basin terrains used for the Equatorial Atlantic propagation from the South to the Central Atlantic. This system had to penetrate far enough at its western end to link two triple junctions on both its sides. While the South and Central Atlantic oceans propagated slowly, they became linked by the Equatorial Atlantic quickly. Whilst the Equatorial Atlantic linked with the South Atlantic at its northernmost tip, it linked with the Central Atlantic northwards of its southern terminus: that is, at the latitude of the future boundary between the Demerara and Guinea plateaus. In order to do this, the Equatorial Atlantic had to penetrate about 1000 km of the oceanic crust of the Central Atlantic to meet its mid-oceanic ridge and to establish a new triple junction. This separated the Offshore Guyana Block, representing the southernmost portion of the pre-late Aptian–Albian Central Atlantic, from the main body of the Central Atlantic, which we know today (Fig. 9a).

The linkage of the Central and South Atlantic resembles a linkage of the tensile fractures in a brittle layer (see Pollard & Aydin 1988) (Fig. 10) where they reach an overstep and the propagation tip of one fracture eventually links with a point inside the other one. Despite differences, the propagation and linkage processes affect brittle layers in both cases, because the observable geometry of the oceanic system is exhibited by the upper crust. One difference, however, is represented by the fact that the Equatorial Atlantic did not propagate through the homogeneous upper-crustal layer: Figure 10 serves as an homogeneous layer analogue. In the Equatorial Atlantic region, the tectonic stresses created a right-stepping system of ENE–WSW dextral strike-slip fault zones. P-shear instead of R-shear orientation of dextral fault zones (sensu Christie-Blick & Biddle 1985; Naylor et al. 1986) indicates that either they were not initiated by transtensional stress or that their positions were affected by prominent crustal weaknesses of NE–SW strikes associated with Proterozoic and Palaeozoic orogenies (e.g. Mascle et al. 1988; Genik 1992; Guiraud & Maurin 2014).
The Late Cretaceous reactivation of the NE–SW-striking Sobral-Pedro II Fault in the Borborema province and the NNE–SSW-striking Pan-African shear zones (Ball 1980; Miranda et al. 1986; Caby 1989) supports the latter argument.

In needs to be emphasized, though, that the southern terminus of the Central Atlantic oceanic segment was not a propagating end of an ocean as it was in the South Atlantic case, while the SW tips of the Gulf of Mexico and proto-Caribbean oceanic segments were. Their ends were controlled by the subduction zone located further SW that prevented them from further propagation. However, these two oceanic corridors were laterally offset such a distance northwestwards that the Central Atlantic segment terminus in the study area looks like the oceanic terminus, which was practically true after the consumption of the proto-Caribbean oceanic region by the end of the Cretaceous.

The Equatorial Atlantic rifting linked the Central Atlantic and propagating South Atlantic during the late Barremian–Aptian/Albian transition. This linkage started to preserve the Central Atlantic terminus in the study area from any potential breaching under far-field stresses characterized by east–west trending extension. The decisive assistance, however, came when the Equatorial Atlantic opened, separating the Offshore Guyana Block from the main body of the Central Atlantic, and rotated it dextrally (Fig. 9a).

The initial separation time of the Offshore Guyana Block from the main body of the Central Atlantic was the time when the entire fault activity in the Offshore Guyana Block stopped. Numerous faults in the distal Guyana transform margin segment also died out during this time. A subsequent progressive dextral rotation of the South American Plate, together with the Offshore Guyana Block, must have brought the strike-slip fault zones of the former (i.e. pre-late Aptian–Albian) ocean segment terminus into less favourable geometries for reactivation by the existing regional stress regime. This is indicated by progressively less and less of them remaining active up to the end of the period between the Aptian–Albian transition and the early Eocene. Coeval seafloor spreading of the Equatorial Atlantic to the south of the main body of the Central Atlantic prevented the Central Atlantic from any potential attempts to propagate further south.

In accordance with observations of multiple dextral strike-slip faults at transform margin segments of the Equatorial Atlantic (e.g. Marinho et al. 1988; Basile et al. 1998; Benkhelil et al. 1998; Nemčok et al. 2013), the separation of the Offshore Guyana Block from the main body of the Central Atlantic by the propagating Equatorial Atlantic must have also been attempted along a system of strike-slip faults, rather than along one single fault. This situation is most probably indicated by a deformation zone that includes several ridges and troughs, which we believe is located to the north of the eastern end of the Accommodation Block. Suggested ridges and troughs are imaged by the free-air gravity map (Fig. 1a) and the reflection seismic images (Fig. 6b) as a system of ENE–WSW- to NE–SW-trending positive and negative anomalies. We assume that it is the highly deformed character of the oceanic crust in this zone that disrupts a typical magnetic-stripe-anomaly image in this small area, causing a mistake in the maps of Müller et al. (1993, 1997), who assigned the Aptian–Santonian age (109–84 Ma) to this piece of oceanic crust (see Fig. 2). Figure 9a indicates that the northern boundary of the Accommodation Block runs SE to meet the SW tip of the Guinea Plateau instead of meeting it at a more northern location. In contrast to the Offshore Guyana Block, we do not have direct well and seismic evidence to support our interpretation of the age of the oceanic crust in this small zone of the Guinea Plateau, but offer an alternative interpretation that better explains the structural architecture imaged by our gravity maps and is in accordance with our interpretation of the development of the Accommodation Block.

Conclusions

The western Demerara and Guyana margin segments, which represent the southern end of the Central Atlantic in the study area, were originally conjugate with North America, the former and latter having an extensional and transform character, respectively. The conjugates were rifted apart in the Jurassic. The NE and eastern Demerara margin segments, which belong to the western portion of the Equatorial Atlantic in the study area, were originally conjugate with Africa. These conjugates were separated from each other in the late Early Cretaceous.

The opening of the Central Atlantic in the study area took place sometimes during the Callovian-Oxfordian. The present-day remnant of the resultant oceanic crust of the Offshore Guyana Block is about 340 km long and located to the NW of the Demerara Plateau.

To the SW of the Offshore Guyana Block, the terminus of the Central Atlantic was formed by a 120–130 km-wide zone of faults dominated by NW–SE-striking strike-slip faults, the eastern portion of which is located in the present-day Guyana transform continental margin segment where the dominating strike-slip faults are sinistral. They represented a portion of the transform arm of the triple junction that linked the southern end of the Central
Atlantic with the northern end of the oceanic corridor in the Gulf of Mexico.

The ocean segment terminus in the study area was characterized by an abrupt northern end to the relatively thick continental crust at its contact with oceanic crust. Its post-break-up evolution was characterized by a lack of any distinct isostatic uplift. All faults of the terminus must have formed an efficient stress-releasing accommodation zone preventing the ocean from further southwards propagation in extension. Attempts of the Central Atlantic to try to propagate further SW along its trend are best indicated by the existence of a few scattered NE–SW-trending rift units that were located both between the strike-slip fault zones of the ocean segment terminus and behind it.

From the late Barremian to the late Aptian–Albian, the northern boundary of the terminus became progressively linked with the propagating tip of the South Atlantic via the Equatorial Atlantic fault system dominated by the east–west-striking dextral strike-slip fault zones arranged in the overall NE–SW trend. The propagation of this linkage started at its eastern end, in the Benue Trough, in the late Barremian. It ran through the Foz do Amazonas Basin region in the west during the late Aptian–Albian. It finished on the continent with the separation of the Demerara and Guinea plateaus from each other. It continued for about 1000 km through the eastern side of the Central Atlantic to meet its seafloor-spreading ridge in order to develop a triple junction.

The linkage trajectory was affected by the pre-existing crustal anisotropy. The Late Aptian–Albian was the time when the last continental bridges of the Equatorial Atlantic, the Guinea Plateau–Demerara Plateau and Pernambuco–Paraiba bridges on the western and eastern ends, respectively, underwent continental break-up.

The rate of Equatorial Atlantic propagation was almost eight times faster than that of the Central Atlantic and almost three times faster than that of the South Atlantic, indicating a rapid linkage of the two relatively slowly propagating oceans. This linkage connected the seafloor-spreading ridge in the northern propagation tip of the South Atlantic with a seafloor-spreading ridge of the Central Atlantic located at the point separating the main body of the Central Atlantic from the Offshore Guyana Block. This separation was instrumental in determining that the southern terminus of the Central Atlantic oceanic segment succeeded in preventing the southern end of the segment from further propagation along trend in extension.

Since the initiation of the South and Central Atlantic linkage via the Equatorial Atlantic, the divergence between North America and South America was subordinate, while the divergences between North America and West Africa, and between South America and Africa, were substantial. Furthermore, the latter two divergence trajectories were not parallel and their rates were different. This difference led to the creation of the Accommodation Block (Figs 1a, 2 & 9a) for the time period until they reached parallelism.

The Accommodation Block was formed at the evolving contact zone between the main body of the Central Atlantic and the Equatorial Atlantic (Fig. 9a). This block was in contact only with oceanic crusts of both oceans. At the beginning of its development, the late Aptian–Albian spreading vector of the Equatorial Atlantic had a NE–SW trend, while that of the Central Atlantic had a roughly east–west trend (Figs 1a & 2). Both oceans progressively reached parallel spreading during the late Aptian/Albian–Paleocene time interval. This took place coevally with the development of the Accommodation Block, which, apart from its growth in an east–west-striking length by accretion, grew in north–south width by the addition of newer and newer stripes to it from the north. In other words, this block was ‘filling the space’ between the two oceans spreading in a divergent pattern.

During the same time, the Offshore Guyana Block was dextrally rotated together with the South American continent with respect to Africa. All of its fault zones died at the start of this rotation, as did the faults of the distal portion of the Guyana transform margin segment. However, its proximal portion was characterized by strike-slip fault zones that progressively died out. This progressive process took place from the beginning of the development of the Accommodation Block to its end, when the last fault zones died out. The progressive dying-out scenario was controlled by the progressive dextral rotation of strike-slip faults of the Guyana transform margin segment away from the correct orientation for their reactivation by existing stress fields.

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