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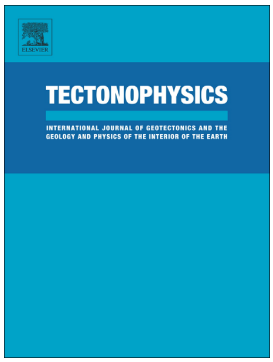

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Post-rift stratigraphic architectures along the African margin of the Equatorial Atlantic: Part I the influence of extension obliquity

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Abstract

We investigated the variability of the first-order crustal structure and early post-rift stratigraphy of six segments of the African Equatorial Atlantic margin using sub-surface data (seismic and wells). Extension obliquity of the segments varies from 0° for the West Ivory Coast and Ghana transform segments to 30° for the Togo-Benin oblique segment and 75° for the East Ivory Coast normally divergent segment. The Sierra Leone and Liberia segments underwent probably deformation during both the early Jurassic rifting of the Central Atlantic and the early Cretaceous rifting of the Equatorial Atlantic with contrasted divergence obliquities. For segments that underwent a single rifting, we show that, the higher the obliquity, the wider the crustal thinning domain. This has a major influence on the first-order geometry of all the post-rift horizons, including the present-day slope: the lower the obliquity, the larger the differential subsidence across the margin and the steeper the present-day slopes of post-rift horizons. This also has a major influence on the flexural isostatic response of the lithosphere to thermal- and erosion/sedimentation- driven (un)loads during the early post-rift. Narrow (transform) segments underwent higher flexural (and/or thermal) uplifts in the proximal domain than wider divergent segments. Along the same margin, divergent segments therefore may preserve early post-rift deposits in their proximal domains, whereas they are not preserved on nearby transform segments.

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1 Introduction

The Equatorial Atlantic Ocean results from a complex rifting of the lithosphere at the junction between the Central and South Atlantic Oceans (Figure 1a). It has evolved from an en-échelon strike-slip system of pull-apart basins to a continental break-up leading to isolated “oceanic basin” patches separated by transform faults (e.g. Mascle et al., 1988; Basile et al., 2005; Heine et al., 2013; Basile, 2015; Ye et al., 2017). These isolated basins ultimately merged to form the conjugate margins boarding the African and South American continents. The African margin of the Equatorial Atlantic Ocean therefore shows a spectacular structure alternating between transform, oblique and normally divergent segments along which the various sedimentary basins underwent contrasting post-rift/transform displacements, accumulation and preservation histories. The kinematic evolution of the Equatorial Atlantic ocean and its margins has been well studied (e.g. Moulin et al., 2010; Heine et al., 2013). Several local studies, most of them focused on the transform segment in Ghana (Figure 1b), pointed out the along-strike structural and stratigraphic variability (e.g., Mascle, 1976; Mascle and Blarez, 1987; Mascle et al., 1986; Benkhelil et al., 1995; Bennett and Rusk, 2002; Blarez and Mascle, 1988; Chierici, 1996; Attoh et al., 2004; Antobreh et al., 2009). However, a systematic large-scale analysis of the first-order characteristics of the crustal structure and stratigraphic evolution of the various segments remains necessary to fully grasp the 3D variability of lithospheric and crustal thinning processes along the margin as well as their implications in terms of crustal geometries and stratigraphic architectures. Indeed, it has been already pointed out that, depending on the kinematic and deformation style, the resulting margins may

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acquire very different present-day geometries (Mercier de Lépinay, 2016). A major difference is that the crustal thinning along transform segments is largely accommodated by transcurrent faults, whereas it is dominantly accommodated by normal faulting along divergent segments. Also, divergent segments typically evolve directly from syn-rift stretching to a post-rift passive margin stage after continental break-up, whereas transform segments may go through an intermediate 'active-transform' stage when the oceanic spreading ridge slides along them (Basile et al., 2005; Nemcok et al., 2016).

The aim of our study is to characterize, using subsurface data (seismic and wells), the first-order structural and stratigraphic features of transform and divergent margin segments along the African Equatorial Atlantic margin from Sierra Leone to Benin (Figure 2). We analyzed their relationships with the obliquity of extension, as well as the impact of crustal thinning pattern and associated vertical displacements on the early post-rift evolution of the sedimentary wedges (Late Cretaceous). This study offers a new large-scale perspective on composite rifted margins with alternating transform and divergent segments along-strike.

2 Regional setting

The African Equatorial Atlantic margin (3-10°N latitude, 20°W-5°E longitude) is separated from the Central Atlantic Ocean by the Guinea Fracture Zone and from the South Atlantic Ocean by the Chain Fracture Zone (Figure 1). This margin bounds the southern West African craton (i.e., the Archean-Paleoproterozoic Leo-Man Shield), which is fringed to the SW and the SE by the Rokelides and

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Dahomeyides Panafrican belts, respectively (Villeneuve, 2005; Villeneuve et al., 2010; Deynoux et al., 2006, Figure 1).

The rift of the Equatorial Atlantic Ocean developed between the Valanginian (ca. 140 Ma) and the Aptian (ca. 112 Ma) as an en-échelon strike-slip system propagating eastward as dextral strike-slip faults (future transforms) and NW- to W-trending normal faults (e.g. Basile et al., 2005; Ye et al., 2017). This rift was connected to an inland rift network of continental scale (Heine and Brune, 2014; Ye et al., 2017). In the Equatorial domain, the rift phase occurred in the Middle Aptian (120-115 Ma, Basile et al., 2005). The breakup of the continent occurred in Late Albian (107-100 Ma), although the age of the first oceanic crust is not well constrained because of the 'Cretaceous Quiet Magnetic Period' (Moulin et al., 2010; Heine et al., 2013). Breakup is marked by a major regional unconformity ("Breakup Unconformity") underlying the latest Albian–Cenomanian marine deposits. This unconformity is also observed on the conjugate Brazilian margins (Zalan and Matsuda, 2007; Trosdtorf Junior et al., 2007; Soares Júnior et al., 2011). At this point, the African equatorial margin had acquired its segmentation with transform segments along former strike-slip faults and divergent segments in between. Mantle exhumation and/or seafloor spreading initiated in isolated "ocean basin" patches that evolved under restricted water circulation during the Albian–Cenomanian (Brownfield and Charpentier, 2006; Gillard et al., 2017).

An 'active-transform' stage may then be locally defined as the oceanic spreading ridge slides along the transform margin segments until at least the Late Santonian (ca. 84 Ma) in Ghana (Basile et al., 2005; Nemcok et al., 2016). A major angular unconformity ("Senonian" Unconformity) was identified as a Turonian-Early

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Santonian hiatus (94-84 Ma) on the shelf in Eastern Ivory Coast and a Santonian-Campanian (86-72 Ma) hiatus in Benin (Elvsborg and Dalode, 1985; Chierici, 1996). It has been associated with the end of the 'active-transform' stage (Brownfield and Charpentier, 2006). Once the oceanic ridges passed beyond the outer corner tip of the transform segments, they entered a passive-margin stage (Basile, 2015).

The two main transform faults (Saint Paul and Romanche transform faults) divide the Equatorial Atlantic margin into three sub- margins: the (i) Guinea-Liberia, (ii) Ivory Coast, and (iii) Ghana-Benin margins, each presenting specific structural features (Figure 1). (i) The Guinea-Liberia sub-margin was probably first rifted during the Central Atlantic formation, before its main rifting phase related to the Equatorial Atlantic (Ye et al., 2017). Indeed, it is located at the junction between the Central and Equatorial Atlantic oceans and several transcurrent faults parallel to the Central Atlantic directions have been proposed in this basin (Bennett and Rusk, 2002). Furthermore, Jurassic siliciclastic sediments and basalts were found in both conjugate margins below syn-rift Lower Cretaceous deposits (Bennett and Rusk, 2002; Figueiredo et al., 2007; Soares Júnior et al., 2011). (ii) The Ivory Coast sub-margin initiated as a pull-apart basin between two transform faults. This margin bears a narrow coastal basin exposing Neogene and Quaternary sediments at the surface (Figure 1). Also, Gillard et al. (2017) suggested that, along this sub-margin, mantle was exhumed at the continent-ocean transition. (iii) The Ghana-Benin sub-margin hosts a wider coastal basin (the Dahomey embayment) preserving Maastrichtian to Cenozoic shallow marine sediments at the surface (Da Costa et al., 2009). Most of the published studies focused on its western tip in Ghana, as it is the continuation of the Romanche transform fault (Mascle and

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Blarez, 1987; Antobreh et al., 2009; Attoh et al., 2004; Davison et al., 2016). More specifically, the Ivory Coast-Ghana marginal ridge located at the outer corner between the Ghana-Benin and the Ivory Coast sub-margins has received renewed attention (Figure 1; Mascle and Blarez, 1987; Mascle et al., 1997; Benkhelil et al., 1997; Clift et al., 1998; Bouillin et al., 1998; Pletsch et al., 2001). Several formation mechanisms have been suggested for that ridge that separates a shallow overhanging marginal basin from the deep oceanic basin, such as crustal thickening, oceanic ridge-related thermal uplift or flexural response of the lithosphere to erosion (Mascle and Blarez, 1987; Sage et al., 2000; Basile and Allemand, 2002; Attoh et al., 2004). This ridge, however, is much localized and disappears rapidly to the West.

3 Material and methods

3.1 Dataset

Our study is based on the interpretation of a large set of subsurface data (hundreds of seismic reflection lines and c. 70 exploration wells) located along the African equatorial margin from Sierra Leone to Benin over an area of c. $2.3x10^5$ km^2 (Figure 2). Half of the wells have been recently re-evaluated in terms of biostratigraphy (palynology, nanofossil, foraminifera dating) by TOTAL. Most of them are located on the shelf and have been used for calibration of stratigraphic surface age. Well-logs (e.g. Gamma Ray, Spontaneous Potential, Sonic, etc…) and cuttings reports were also used for lithologic and paleo-environment interpretation (Van Wagoner et al., 1988, 1990; Homewood et al., 1992). We present here 9 regional composite dip-sections extending from the present-day

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shelf to the abyssal plain and highlighting the main structural and stratigraphic characteristics of each margin segment (Figure 2).

3.2 Structural and stratigraphic interpretations

On those sections, we interpreted four crustal domains using definitions of Peron-Pinvidic et al. (2013) and Sutra et al. (2013) and mapped them across the studied area (Figure 2). These are (i) the continental thinning domain, (ii) the hyper-extended continental domain, (iii) the mantle exhumation domain and (iv) the oceanic domain. The thinning domain was mapped where the continental crust is significantly stretched and thinned from an initial thickness (~50km for a craton) to ~10km by normal faulting for divergent segments or the extensional component of transtensional faulting for transform segments. It usually includes a proximal domain where the crustal thinning is moderate and a necking domain where the continental crust is thinned rapidly seaward. As the bottom of continental crust is rarely imaged on seismic reflection data, the identification of the limit between the proximal and the necking domains has been mainly based on the Breakup Unconformity geometry where a slope rupture occurred indicating the beginning of strong thinning. The hyper-extended domain was identified as the domain of extremely thinned continental crust (≤ 10 km thick; Sutra et al., 2013). Faults are not always well imaged within this domain, so we usually use the geometry of the Moho reflector to map it. Mantle exhumation was sometimes observed at the transition between the hyper-extended and oceanic domains (Gillard et al., 2017).

We mapped the crustal domains on the 5 margin segments: West Ivory Coast (WIC), East Ivory Coast (EIC), Ghana (GN), Togo-Benin (TG-BN), Sierra

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Leone (SL) and Liberia (LB; Figure 2). For each segment, we also measured (i) the cross-width of the thinned continental domain (thinning plus hyper-extended domains (Figure 2), which is a minimum value since the thinning domain may begin further inland, (ii) the cross-width of the mantle exhumation domain for the EIC segment, (iii) the approximate obliquity of extension with respect to the Equatorial Atlantic opening direction, i.e. the angle between the transform faults and the segment direction (Table 1, Figure 2). The segment's direction is defined by the strike of the Continent-Ocean Boundary (COB) i.e., the limit between the oceanic and the exhumation domains or between the oceanic and continental domains if the exhumation domain is absent (Figure 2). For the Sierra Leone and Liberia segments, we also measured (iv) the extension obliquity with respect to the Central Atlantic opening direction (Table 1).

We then classified the segments as transform or divergent according to their extension obliquity: transform segment obliquity ranges from 0° to 15° (Mercier de Lépinay et al., 2016), and divergent segment obliquity is higher. In the latter case, we differentiated normally divergent segments with obliquity higher than 75° and oblique segments otherwise (15°-75°).

We mapped four regional early post-rift Upper Cretaceous horizons (c. 104-66 Ma) in each basin (Figures 3 to 5): (i) the Late Albian Breakup Unconformity (BU, c. 104 Ma) marking the end of continental Equatorial Atlantic rifting and correlated seaward with the diachronous oceanic crust; (ii) the major Cenomanian-Turonian maximum flooding surface (c. 94 Ma); (iii) the Senonian Unconformity (probably Intra-Santonian, ca. 84 Ma) along the East Ivory Coast, Ghana and Togo-Benin segments, or its Santonian equivalent along Sierra Leone and Liberia

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segments; (iv) the base of Cenozoic (66 Ma). The late post-rift Cenozoic wedge (66-0 Ma) was not studied in detail in this work.

4 Segment structures and early post-rift stratigraphic architectures

4.1 West Ivory Coast segment

The West Ivory Coast (WIC) segment is a transform segment (0° obliquity) connected to the Saint Paul transform (Figure 2). Rift-related strike-slip and normal faulting affects a narrow strip of continental crust (~50 km, Table 1) resulting in a sharp transition from the thinning to the oceanic domains (Figure 3a). In the proximal thinning domain, the Breakup Unconformity is shallow, smooth and slightly flexed seaward (Figure 3a). Seaward, the crust thins rapidly (over c.30 km) with deeply sited normal faults (necking domain) and the Breakup Unconformity dips very steeply seaward. Under the unconformity, a rift-related normal/transtensional fault was locally reactivated during the Late Cretaceous (Figure 3a), forming an anticline parallel to the segment's direction (Figure 2).

The early post-rift (Upper Cretaceous) sediments are preserved only in the necking and oceanic domains, not in the proximal thinning domain (Figure 3a). Upper Cretaceous sediments onlap the Breakup Unconformity landward in the necking domain, and the lower section of Upper Cretaceous units downlaps the oceanic crust (Figure 3a). The late post-rift (Cenozoic) wedge, on the other hand, is preserved across the whole margin from the proximal to the oceanic domains.

4.2 East Ivory Coast segment

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The East Ivory Coast (EIC) segment is a normally divergent segment (75° obliquity). It is oriented NW-SE and connects the WIC transform segment and the Ghana transform segment (Figure 2). Four main crustal domains are distinguished (Figures 2, 3b and 3c). (i) The thinning domain shows steep normal faults with a probable minor strike-slip component (Figures 3b and 3c). (ii) The hyper-extended domain is well identified (the Moho is undulated and offset by faulting), although its internal structure is not well imaged with probably the presence of syn-rift sediments. The width of the thinned continental domain (thinning plus hyperextension) increases from the NW to the SE up to 240 km (Figure 2; Table 1) and is much wider than along the WIC segment (c. 50 km). (iii) The mantle exhumation domain is 80-100 km wide and associated with volcanism preceding the distal (iv) oceanic domain (Figure 2, Table 1, Gillard et al., 2017).

As a difference with the WIC segment, the Upper Cretaceous sedimentary wedge is preserved everywhere across the margin, from the proximal to oceanic domains as well as the late post-rift (Cenozoic) wedge (Figure 3c). The proximal wedge on the paleo-shelf shows five major transgressive/regressive cycles with a mean duration of 6-7 Ma and it includes the Senonian Unconformity (Intra-Santonian, c. 84 Ma) associated with a downward shift (> 200m) of the offlap breaks trajectory. Upper Cretaceous deposits may also have been locally eroded away by Cenozoic slumping in the region close to the inner corner of the margin (Figures 2 and 3b). Thus, during the Late Cretaceous, accommodation creation history in the proximal domain has allowed for the preservation of fluvial-deltaic to shelf deposits and has nonetheless recorded a transient accommodation reduction associated with the Intra-Santonian unconformity (Figure 3c).

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4.3 Ghana segment

The Ghana segment is a transform segment (0° obliquity) connected to the Romanche fault (Figure 2, Table 1). It displays features similar to the WIC transform segment. (i) There is no hyper-extended domain, and the necking domain connects directly to the oceanic domain (Figure 4a & b). (ii) The rift-related strike-slip/normal faults (necking domain) affect a narrow strip (50-100 km, Table 1), deforming thick pre-rift deposits (probably Paleozoic in age; Figure 4a, Mascle and Smit, 1974). Note that the present-day shelf is restricted to the proximal domain, which widens from the East to the West, resulting in a non-cylindrical present-day platform (Figure 2). (iii) The early post-rift sediments are preserved only on the necking and oceanic domains (Figure 4b). (iv) Upper Cretaceous sediments onlap the Breakup Unconformity landward in the necking domain, and the Cenomanian-Santonian units downlap the oceanic crust seaward (Figures 4b). (v) The Cenozoic wedge, on the other hand, is preserved across the entire margin.

The Ghana marginal ridge is located at the junction between the EIC divergent segment and the Ghana transform segment (Figures 2 and 4a). Onlaps of Upper Cretaceous units upon the Late Albian Breakup Unconformity indicate that this high relief existed since at least the Late Albian (Bouillin et al., 1998; Basile et al., 1993; Antobreh et al., 2009). Downward curved onlaps suggest differential subsidence of the marginal ridge, which was probably increasing landward during the Late Cretaceous. Folding associated with the reactivation of syn-rift faults is observed in the thinning domain until at least the Early Santonian.

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The Ghana marginal ridge is restricted and characteristic of the outer corner of the margin.

4.4 Togo-Benin segment

The Togo-Benin segment is an oblique segment (30° obliquity to the Romanche transform fault; Figure 2). Its necking domain (70-190 km, Table 1) is wider than along the WIC and Ghana transform segments, but narrower than along the normally divergent EIC segment. No hyper-extended or mantle exhumation domain has been observed (Figure 4c). Necking is mostly accommodated by normal faulting although normal faults may have strike-slip components. Along the Romanche transform fault, anticlines affecting the early post-rift sediments mark the reactivation of syn-rift faults during at least the Late Cretaceous (Figures 2 and 4c) similarly to the WIC transform segment. Onshore, post-early Paleogene offsets and seismicity on faults connected to transforms also indicate very late post-rift reactivations (e.g. Bellion et al., 1984; Bellion and Robineau, 1986; Meghraoui et al., 2016).

Most of the early post-rift sediments are preserved in the necking and oceanic domains (Figure 4c). Only thin Upper Santonian-Maastrichtian (84-66 Ma) shallow marine deposits are preserved in the proximal domain and extend into the onshore Dahomey Embayment (Figure 2). The late post-rift Cenozoic sedimentary units are preserved over the whole margin, including in the Dahomey Embayment. As with the WIC and Ghana transform segments (Figures 3a and 4b), the early post-rift deposits onlap landward on to the Breakup Unconformity in the thinning domain and the Cenomanian-Lower Santonian units downlap partly seaward on to

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the oceanic crust (Figure 4c). Consequently, the oblique Togo-Benin segment shares several similarities with other transform segments, suggesting a major influence of the Romanche Transform Fault on its crustal structure and early post-rift stratigraphy.

4.5 Sierra Leone segment

The Sierra Leone segment forms the southern margin of the Sierra Leone Plateau (Figures 1 and 2). It is a polyphased segment, as it probably rifted first during the Central Atlantic rifting as a transform segment (0° obliquity), and was later reactivated during Equatorial Atlantic rifting as an oblique segment (25° obliquity, Table 1). It comprises only three crustal domains: (i) thinning domain (proximal plus necking), (ii) hyper-extended domain and (iii) oceanic domain (Figures 2, 5a and 5b). In the thinning domain, the southeastern part underwent mostly normal faulting forming titled blocks (Figure 5b), whereas the northwestern part of the segment underwent strike-slip faulting with less tilted blocks but strong and steep faults offsetting pre-rift strata (Figure 5a). The width of thinning domain is similar to that of the Togo-Benin oblique segment (70-150 km, Table 1) and narrows towards the Liberia segment in the Southeast (Figure 2). Syn-rift normal faults have been locally inverted during the Late Cretaceous (Figure 5b). Upper Cretaceous post-rift units are only preserved in the necking and oceanic domains, not in the proximal domain (Figures 5a and 5b). The Breakup Unconformity dips steeply seaward in the necking domain and the early post-rift deposits onlap the BU or the syn-rift (Barremian?-Late Albian) paleo-structural highs (Figure 5b). They do not downlap upon the oceanic crust seawards. In contrast, the late post-rift

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(Cenozoic) units are preserved everywhere across the margin, from the proximal to the oceanic domains and they are incised by numerous canyons on the continental slope (Figures 5a and 5b).

4.6 Liberia segment

The Liberia segment experienced probably oblique rifting during the Central (25° obliquity) and the Equatorial Atlantic openings (50° obliquity, Figure 2). It shows a continental thinning domain and an oceanic domain (Figure 6c). Although the faults are not well imaged, the thinning domain is as narrow (50-80 km) as in the transform segments (Table 1). As along the WIC and Ghana transform segments, no Upper Cretaceous sediments are preserved in the proximal domain, and lower units of Upper Cretaceous deposits show seaward dipping reflectors, with downlaps on the oceanic crust. As Upper Cretaceous units pinch out landward usually at the same location and thicken seaward (Figure 5c), the Liberia segment differs from other segments by this fan shape of its Upper Cretaceous wedge. No major reactivation of syn-rift faults was observed. The Cenozoic sedimentary wedge shows a different geometry with a shelf developed in the proximal domain and deep basin units in distal domains.

4.7 Summary

Our observations show that the various segments of the African margin of the Equatorial Atlantic have contrasted crustal structures and early post-rift (Upper Cretaceous) stratigraphic architectures (Figure 6). (i) The West Ivory Coast and Ghana transform segments have a narrow thinning domain resulting from strike-

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slip and, to a lesser extent, normal faulting. Their thinning domain is directly connected to an oceanic domain without any hyper-extended or exhumation domains (Figures 3a, 4b and 6). Their early post-rift wedges are not preserved in the proximal domain. They show landward onlaps in the necking domain and seaward downlaps in the lower section of the wedge (Figure 6). (ii) By contrast, the normally divergent East Ivory Coast segment is composed of four crustal domains: the continental thinning domain bearing a coastal basin, the hyper-extended continental domain, the mantle exhumation domain and the oceanic domain (Figures 3b and 3c). Early post-rift sedimentary units are preserved across the whole margin, from the proximal to oceanic domains, indicating enough accommodation creation in the proximal domain since the breakup to allow for their preservation (Figure 4c). (iii) The oblique Togo-Benin segment displays mixed features. Like normally divergent segments, its thinning is mainly accommodated by normal faults and bears a fairly wide coastal basin (up to c. 110 km). Like transform segments, it does not show a hyper-extended domain (the narrow necking and oceanic domains are juxtaposed) and the early post-rift units onlap landward in the necking domain and downlap partly seaward in the oceanic domain. (iv) the Sierra Leone and Liberia polyphased segments show specific features: syn-rift tilted blocks with landward dipping faults and a fan-shaped early post-rift wedge (Figures 5c and 6). (v) Along all types of segment, the Cenozoic wedge is preserved across the whole margin.

5 Implications and discussion

5.1 Obliquity of extension and crustal thinning distribution

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Segments of the African margin of the Equatorial Atlantic show that: the higher the extension obliquity, the wider the crustal thinning domain (Table 1). Indeed, the normally divergent segment (EIC), with the highest extension obliquity (75°), shows the widest crustal thinning domain (160-240 km). It is associated with a wide mantle exhumation domain (80-100 km, Gillard et al., 2017) and a diffuse continent-ocean boundary (COB). Conversely, the transform segments (WIC and Ghana), with the lowest extension obliquity (0°), show narrowest crustal thinning domains (50-100 km) and very sharp continent-ocean transitions. The oblique divergent segment (Togo-Benin), with an intermediate extension obliquity (30°), has an intermediate width of crustal thinning domain (70-190 km).

This configuration seems nonetheless restricted to segments that underwent a single rifting event. Indeed, the Sierra Leone and Liberia segments, which underwent deformations with different obliquities during the Central and the Equatorial Atlantic riftings, do not show this trend. The width of the crustal thinning domain of the Sierra Leone segment falls in the range of oblique segments although it was a transform segment during the Central Atlantic rifting (Table 1). Similarly, the oblique Liberia segment is as narrow as transform segments (Table 1). Segments that underwent two rifting events may have been weakened by the early Central Atlantic rifting before their main Equatorial Atlantic rifting allowing for the localization of crustal deformation into a narrow domain. Nonetheless, the role of pre-existing structures (e.g. Panafrican belts) on obliquity and crustal thinning remains unclear, especially for polyphased segments (e.g., the Liberia segment, Figure 5c). Furthermore, the reason why obliquity varies among segments may be related to a complex interference between far-field plate force induced plate

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relative displacements, lithospheric heterogeneity and deep mantle motions (Koptev et al., 2015, 2016), which remains to be investigated.

Syn-rift extension obliquity is therefore a fundamental parameter defining the first-order crustal structure of the segments. For segments resulting from a single rifting event, it can be used to predict crustal thinning width in first order.

5.2 Obliquity of extension and differential subsidence

The post-rift differential subsidence between the proximal and the distal parts of rifted margins is commonly interpreted to be controlled by thermal subsidence. For margin segments resulting from a single event of rifting, thermally driven differential subsidence rates increase seaward along with the thinning of the lithosphere and decrease through time as the thinned lithosphere equilibrates thermally (e.g. Rouby et al., 2013). Indeed, for all post-rift horizons, including the present-day continental slope, transform segments show the steepest seaward dipping horizons, whereas the normally divergent segment has the gentlest, although the slope could be apparent as the used seismic lines were not all perpendicular to margin (Figure 7). So, for segments that underwent a single rifting, the narrower the necking domain of the segment, the narrower the domain accommodating the thermal driven differential subsidence, the steeper the slope of post-rift horizons.

Here again, segments that underwent successive rifting do not follow this relationship: both show present-day slopes of post-rift horizons as steep as those of transform segments (Figure 7). This is probably because a lithosphere that has

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been thinned twice does not equilibrate thermally in the same way than single rifting margins.

5.3 Obliquity of extension and first order stratigraphic post-rift architecture

Our study shows a much contrasted preservation of the early post-rift sedimentary wedge in the proximal domains between divergent and transform segments. As a difference, the preservation of the late post-rift Cenozoic sedimentary wedge is much more homogeneous across and along the margin.

We identified two end-member behaviors during the early post-rift: (i) the normally divergent segment preserved most of the early post-rift deposits in the proximal domain and the coeval distal wedge is conformable on the oceanic crust seaward; (ii) transform segments lack most of early post-rift sediments in the proximal domain and the equivalent distal wedge onlaps the Breakup Unconformity landward and downlaps the oceanic crust seaward (especially its lower section). This contrast in the preservation implies distinct vertical displacement and accommodation histories in the proximal domain of transform and divergent segments during the early post-rift (Figure 8). (i) The normally divergent segment sustained enough accommodation in the proximal domain throughout the Upper Cretaceous to preserve the early post-rift sedimentary wedges (Figure 8a-d). (ii) As a difference, transform segments experienced accommodation reduction in the proximal domain during at least part of the early post-rift, triggering sediment erosion (Figure 8e-h). According to unpublished vitrinite reflectance data (in-house Total) from numerous wells, a part of latest syn-rift and/or early post-rift Upper Cretaceous deposits are probably missing due to erosion in the proximal domains

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of transform segments, which is estimated up to more than 1000 m in Ghana plateau.

These distinct behaviors cannot be explained by the contrast in thermally driven differential subsidence between transform and normally divergent segments. Indeed, thermally driven subsidence neither induces uplift in the proximal domain nor transient decrease in subsidence rates. The timing of the early post-rift erosion/by pass in the proximal domain of transform segments falls within the same time interval as the Senonian Unconformity (ca. 86-83Ma) that eroded away some of the early post-rift sediments in the proximal domain of the margin. However, the unconformity alone cannot explain the absence of most of the proximal early post-rift deposits along transform segments because the unconformity is recorded, with various incision amplitudes, along segments of all types. The driving mechanism is either independent on or amplifying the impact of the Senonian unconformity.

The accommodation reduction in the proximal domain of transform segments during the early post-rift may therefore be driven by either (i) a flexural uplift at the transition of the un-deformed and the proximal domains or (ii) the thermal uplift during the active transform stage:

(i) The post-rift evolution of rifted margins is indeed also partially controlled by the flexural response to thermal load and erosion/accumulation processes (e.g. Rouby et al., 2013). For thermal subsidence, this flexural uplift is expected to be continuous and to decrease in amplitude through time as the thinned lithosphere equilibrates thermally (e.g., Van der Beek, 1994; Rouby et al., 2013). However, by contrast to thermal subsidence, flexure induces uplift at the transition between the

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undeformed and the proximal domains (‘rift shoulder’, e.g. Watts, 2001; Van der Beek et al., 1994, Van der Beek et al., 2001) and amplifies locally the subsidence at the transition between the necking domain and the hyperextended or oceanic domain (e.g. Watts, 2001; Rouby et al., 2013).

The differential preservation pattern between transform and divergent segments suggests a higher and probably more durable flexural uplift along transform segments than divergent segments in proximal domain. This is consistent with the difference in width of the thinning domain of those segments (narrower for transform and wider for divergent). Indeed, the narrower the thinning domain, the higher the associated flexural uplift (e.g. Van der Beek et al., 1994; Rouby et al., 2013), the longer the time needed for equilibrium. Thus, along transform segments, the flexural uplift could have driven directly the accommodation reduction causing erosion or bypass of the syn- and/or early post-rift sediments. Erosional unloading in turn could have amplified furthermore the flexural uplift along the transform border by isostatic compensation, which could have intensified the coeval accommodation reduction during the Santonian unconformity.

Along transform segments only, the earliest post-rift (pre-Santonian) distal wedge onlaps the Breakup Unconformtity landward and downlaps the oceanic crust seaward (Figure 8e-h). These downlap geometries may however be apparent, as they may be initially onlaps subsequently rotated by differential subsidence into downlaps (Figure 8g-f). In this case, those seaward downlaps and landward onlaps suggest that, in the earliest post-rift, the distal continental margin was slightly deeper than the newly formed oceanic crust, defining local and distal depot-center

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(Figure 8g). This depot-center is consistent with the flexure of the margin with narrow thinning width that compensates the proximal uplift with a distal local amplification of the subsidence (Rouby et al., 2013).

This flexure-driven accommodation reduction is also consistent with the later preservation of the late post-rift wedge along transform segments. Indeed, it can be interpreted as a transition from uplift to subsidence in the proximal domain (i.e. accommodation reduction to creation) resulting from the decrease in thermal load of the lithosphere with time that decreases the flexure and the uplift as well.

Finally, this flexure driven accommodation reduction is consistent with the fact that, the general accommodation creation in the proximal domain of the normally divergent segment during the early post-rift, which does not preclude transient accommodation reductions over that period. Indeed, the Santonian unconformity and lowstand wedge is documented in the proximal domain of the normally divergent segment. The driving mechanism of the Santonian unconformity remains nonetheless to be determined (absolute sea level fall, geodynamic change-inversion of the Benue Through, transition from active transform to passive margin state, etc.,), which is beyond the scope of our study.

(ii) An alternative, and yet not mutually exclusive, explanation would be that during the active transform stage, heating from hot oceanic lithosphere triggers potentially significant thermal uplift of continental lithosphere along transform segments, whose magnitude varies depending on locations at the margin (Gadd and Scrutton, 1997). However, this uplift would be mainly restricted to the active transform stage (until 84 Ma for the Ghana segment**;** Basile et al., 2005), instead of lasting until the end of the early post-rift. A Late Cretaceous cooling has been

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documented by thermochronology along the Ivory Coast-Ghana marginal ridge (Clift et al., 1998; Bouillin et al., 1998; Bigot-Cormier et al., 2005), which could have postdated a heating resulting from the passage of the hot accretion axis along the transform (Bouillin et al., 1998). However, others debated the origin of the cooling with a retrogressive erosion-induced flexural uplift (Bigot-Cormier et al., 2005).

6 Conclusion

We analyzed the first-order variability of the crustal and early post-rift stratigraphic structures along six segments of the African Equatorial Atlantic margin (West Ivory Coast, East Ivory Coast, Ghana, Togo-Benin, Sierra Leone and Liberia segments) using sub-surface data.

(1) For segments that underwent a single rifting episode, extension obliquity influences the crustal thinning distribution across the margin: the higher the obliquity, the wider the thinned continental domain (spanning both the thinning and hyper-extended domains). Thus divergent segments (75-90° obliquity) show a wide thinned continental domains (160-240 km) whereas transform segments (0° obliquity) show sharp transitions to the oceanic domain (50-100 km).

(2) Rift extension obliquity strongly influences the differential subsidence of the margin segments throughout their post-rift evolution and in doing so impact the first-order post-rift stratigraphic architectures: the lower the obliquity, the steeper the present-day slopes of all post-rift horizons.

(3) Rift extension obliquity, via the crustal thinning distribution, also strongly influences the flexural isostatic response of the lithosphere during the early post-rift: narrower transform segments show higher flexural uplift, and so they do not

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preserve early post-rift deposits in the proximal domain, whereas wider divergent segments, with limited flexural uplift, allow for the preservation of the early post-rift sedimentary wedge across the whole margin.

Similar analysis of the South American conjugate margin should provide further constraints on observed relationships between extension obliquity and the first-order crustal and early post-rift stratigraphic features, and test the potential symmetry/asymmetry processes compared to Africa. Compilation of these features for other margin segments worldwide would help refining the range of thinning width for each segment type and allow for the predictive relationships to be validated.

Acknowledgments

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Figures & Captions

Figure 1: (a) Geographic context of the Equatorial Atlantic Ocean. (b) Simplified geological map of the African Equatorial Atlantic margin and its continental hinterland (after Ye et al., 2017). Its location is indicated by a yellow box in Figure 1a. FZ: Fracture zone.

Figure 2: (a) Location of the regional seismic sections (in red) over a map showing the main structural domains of the margin. Structures and onshore geology are taken from Figure 1b. Localities are those shown in Figure 1b. (b) Map of the studied margin segments classified according to their types and measured extension obliquity. SL: Sierra Leone Segment. LB: Liberia Segment. WIC: West Ivory Coast Segment. EIC: East Ivory Coast Segment. GN: Ghana Segment. TG-BN: Togo-Benin Segment. DA: Dahomey embayment. COB: Continent-ocean boundary. FZ: Fracture zone.

Figure 3: Interpreted regional cross-sections of the West Ivory Coast transform segment (a) and the West Ivory Coast normally divergent segment (b & c). See location on Figure 2.

Figure 4: Interpreted regional cross-sections of the Ivory Coast-Ghana marginal ridge (a) at the outer corner, the Ghana transform segment (b) and the Togo-Benin obliquely divergent segment (c). See location on Figure 2.

Figure 5: Interpreted regional cross-sections of the Sierra Leone segment (a & b) and the Liberia segment (c). See location on Figure 2.

Figure 6: Synthetic chart summarizing the deformation style of each segment (transform, oblique, normally divergent or polyphased), their first-order synthetic lithologic log in the proximal shelf area and their schematic depositional patterns (depositional environment & present-day wedge geometry). The regional deformation regimes for the Equatorial Atlantic margin and the Central Atlantic rifting are also indicated.

Figure 7: Compilation of the two-way time (TWT)/distance geometry of three major horizons: (a) the seafloor, (b) the base of the Cenozoic horizon and (c) the Breakup unconformity along each segment of the African Equatorial margin. They are superposed at the limit of proximal and necking domains.

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Figure 8: Schematic evolution of the post-rift vertical displacements along divergent (a-d) and transform (e-h) segments. See Section 5.3 for details.

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Table

Table 1: Margin segment structural features compilation, including margin type, measured extension obliquity with respect to the Equatorial and/or Central Atlantic opening direction, width of the thinned continental domain (spanning thinning and hyper-extended domains) and width of mantle exhumation domain. EA: Equatorial Atlantic opening; CA: Central Atlantic opening.

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TABLE 1. COMPILATION OF SEGMENT STRUCTURAL FEATURES

Segment Name	Margin Type	Extension Obliquity	Thinned Continent Width (km)	Mantle Exhumation Width (km)
West Ivory Coast	Transform	0°/EA	50	/
Ghana	Transform	0°/EA	50-100	/
Togo-Benin	Oblique	30°/EA	70-190	/
East Ivory Coast	Normally Divergent	75°/EA	160-240	80-100
Sierra Leone	Polyphased	25°/EA; 0°/CA	70-150	/
Liberia	Polyphased	50°/EA; 25°CA	50-80	/

Table 1: Margin segment structural features compilation, including margin type, measured extension obliquity with respect to the Equatorial and/or Central Atlantic opening direction, width of the thinned continental domain (spanning thinning and hyper-extended domains) and width of mantle exhumation domain. EA: Equatorial Atlantic opening; CA: Central Atlantic opening.

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Highlights:

- Extension obliquity influences the structures and stratigraphic architectures of the African Equatorial Atlantic margin
- Crustal thinning width increases from transform to normally divergent segments, as obliquity increases
- The lower the obliquity, the steeper the present-day slopes of post-rift/transform horizons
- Divergent segments preserve early post-rift deposits in proximal domain, whilst transform segments don't, due to probably different flexural and/or thermal uplifts

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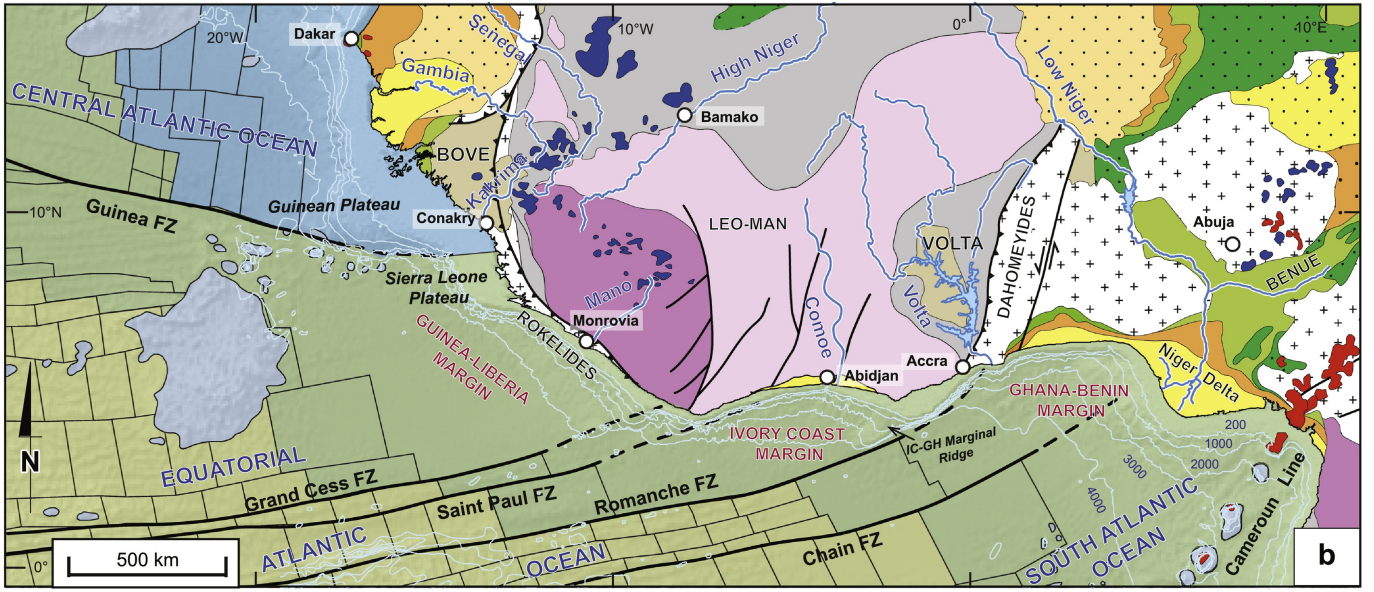

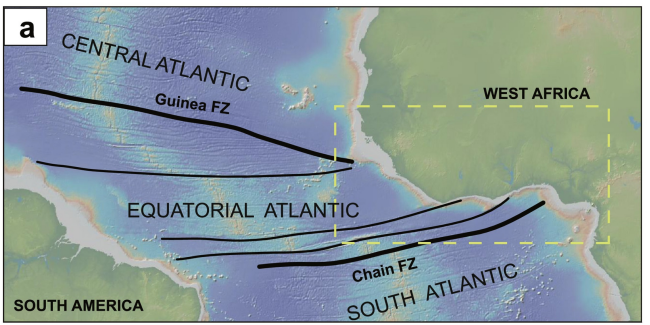

VOLCANICS and PLUTONS
- Cenozoic
- Mesozoic

OCEANIC CRUST
- Cenozoic
- Cretaceous
- Jurassic
- Oceanic plateau

SEDIMENTARY COVER
- Continental deposits
- Neogene
- Late Eocene - Oligocene
- Paleocene - Eocene
- Upper Cretaceous
- Lower Cretaceous
- Paleozoic
- Neoproteozoic - Cambrian

CRYSTALLINE ROCKS
- Panafrican & Variscan mobile belts
- Paleoproterozoic basement
- Archean basement

- River
- Lake
- Meso-Cenozoic fault
- Transform fault

Figure 1

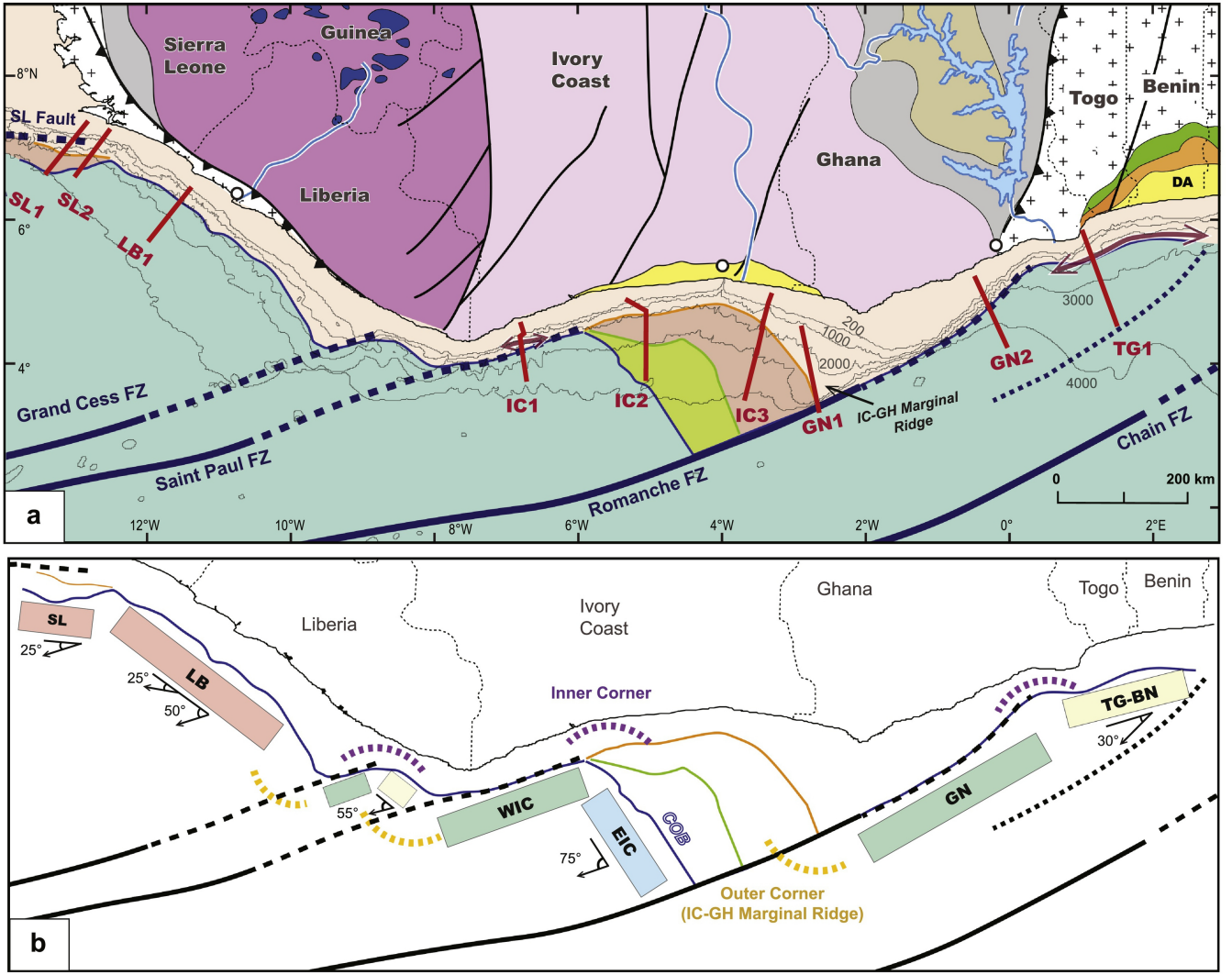
Sierra Leone
Guinea
Liberia
Ivory Coast
Ghana
Togo
Benin
DA
SL Fault
SL1
SL2
LB1
IC1
IC2
IC3
GN1
GN2
TG1
IC-GH Marginal Ridge
Grand Cess FZ
Saint Paul FZ
Romanche FZ
Chain FZ
200
1000
2000
3000
4000
8°N
6°
4°
12°W
10°W
8°W
6°W
4°W
2°W
0°
2°E
0
200 km
a
SL
LB
25°
50°
55°
75°
30°
WIC
EIC
COB
GN
TG-BN
Inner Corner
Outer Corner
(IC-GH Marginal Ridge)
b
STRUCTURAL DOMAINS OF THE MARGIN
Continental Thinning Domain
Hyper-extended Continental Domain
Exhumation Domain
Oceanic Domain
Thinned/Hyper-extended Domains' Limit
Hyper-extended/Exhumation Domains' Limit
COB
Offshore Anticline
Inner Corner
Outer Corner
SEGMENT TYPES
Transform
Oblique
Normally Divergent
Polyphased

Figure 2

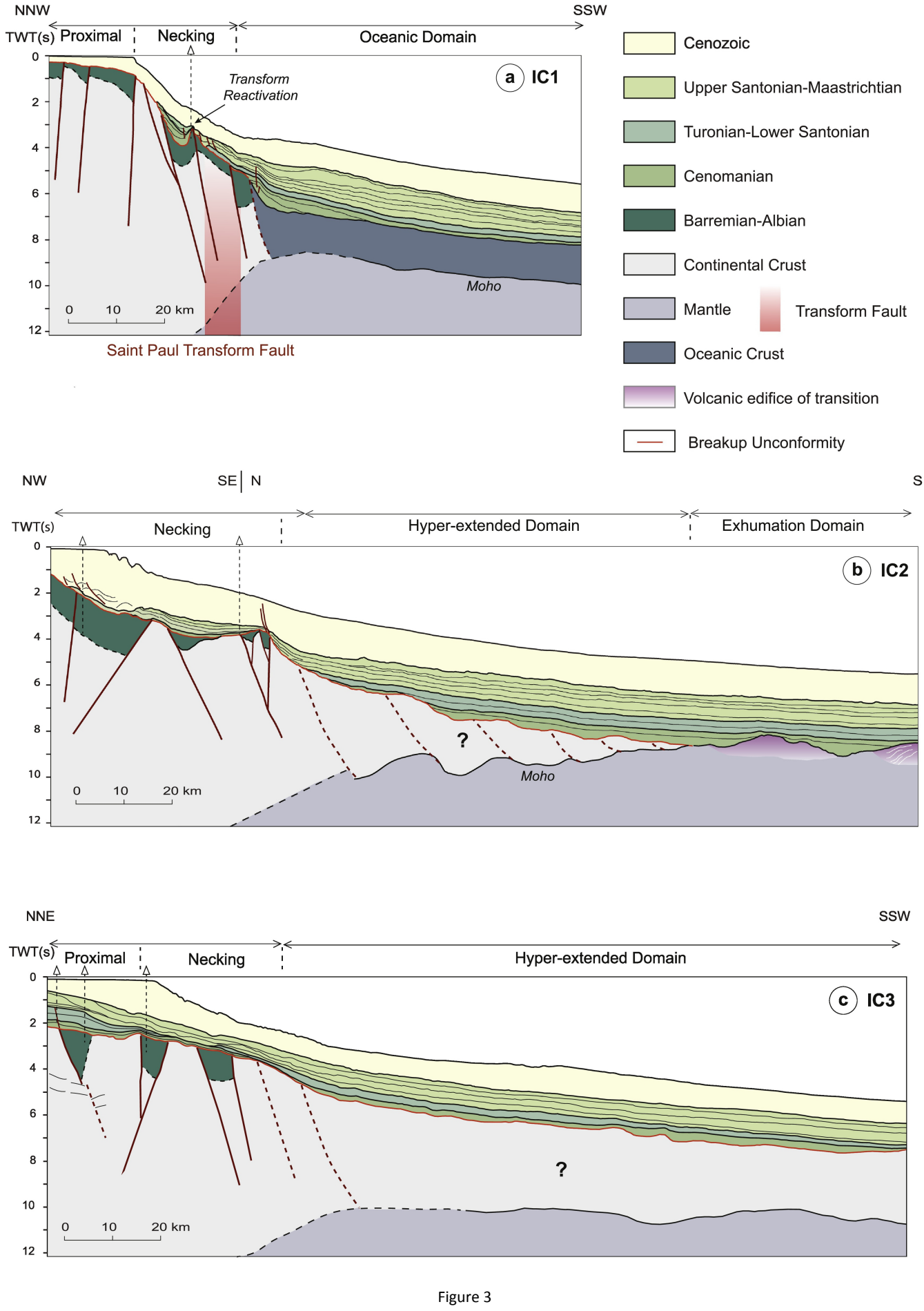
NNW
SSW
TWT(s)
Proximal
Necking
Oceanic Domain
a IC1
Transform Reactivation
Moho
0 10 20 km
Saint Paul Transform Fault
Cenozoic
Upper Santonian-Maastrichtian
Turonian-Lower Santonian
Cenomanian
Barremian-Albian
Continental Crust
Mantle
Transform Fault
Oceanic Crust
Volcanic edifice of transition
Breakup Unconformity
NW
SE
N
S
Necking
Hyper-extended Domain
Exhumation Domain
b IC2
?
Moho
NNE
SSW
Proximal
Necking
Hyper-extended Domain
c IC3
?

Figure 3

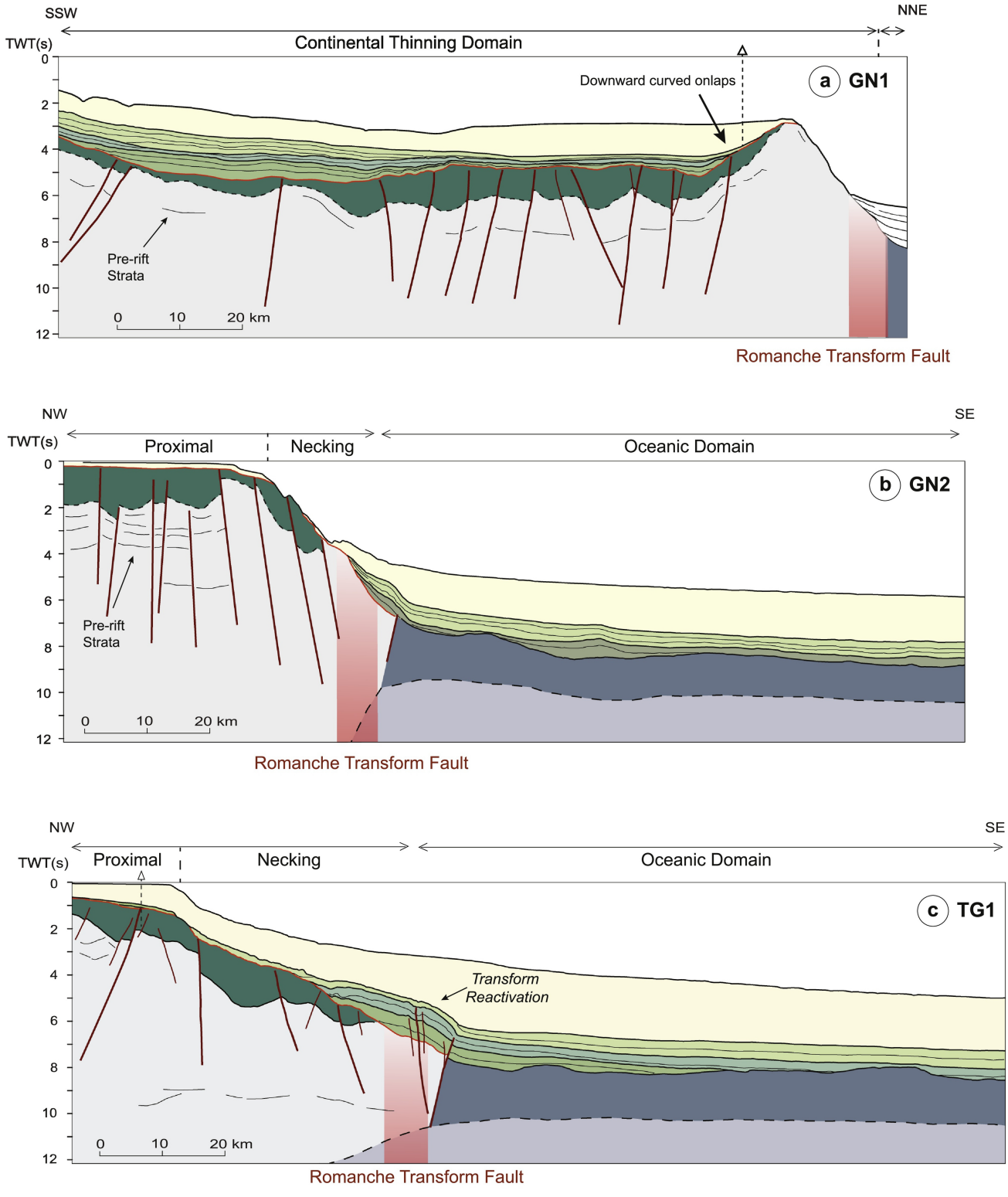
SSW
NNE
TWT(s)
Continental Thinning Domain
Downward curved onlaps
a GN1
Pre-rift Strata
0 10 20 km
Romanche Transform Fault
NW
SE
TWT(s)
Proximal
Necking
Oceanic Domain
b GN2
Pre-rift Strata
0 10 20 km
Romanche Transform Fault
NW
SE
TWT(s)
Proximal
Necking
Oceanic Domain
c TG1
Transform Reactivation
0 10 20 km
Romanche Transform Fault
Cenozoic
Upper Santonian-Maastrichtian
Turonian-Lower Santonian
Cenomanian-Santonian
Cenomanian
Barremian-Albian
Continental Crust
Mantle
Oceanic Crust
Breakup Unconformity
Transform Fault

Figure 4

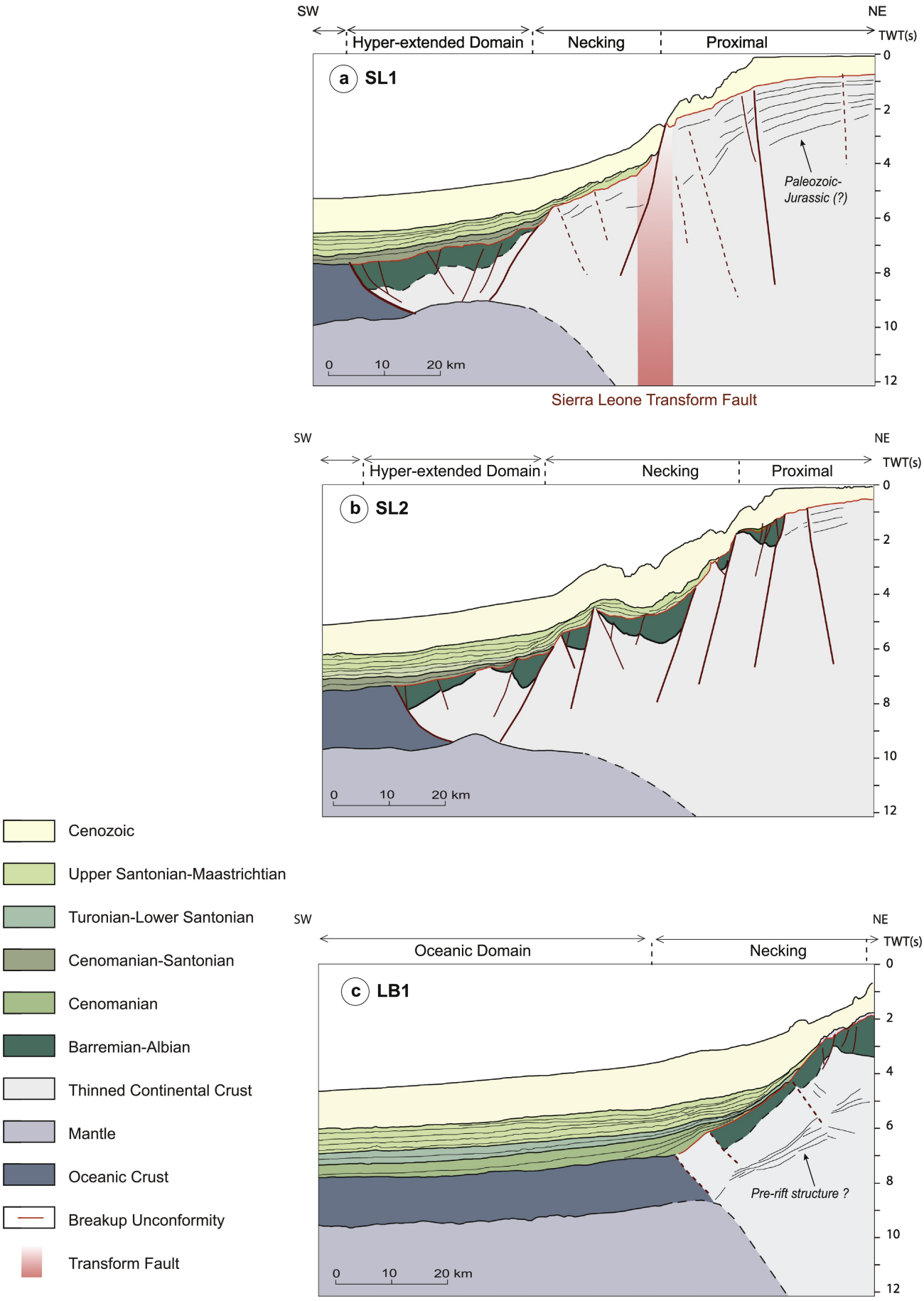
SW
NE
Hyper-extended Domain
Necking
Proximal
TWT(s)
a SL1
Paleozoic-
Jurassic (?)
0
10
20 km
Sierra Leone Transform Fault
b SL2
Oceanic Domain
c LB1
Pre-rift structure ?
Cenozoic
Upper Santonian-Maastrichtian
Turonian-Lower Santonian
Cenomanian-Santonian
Cenomanian
Barremian-Albian
Thinned Continental Crust
Mantle
Oceanic Crust
Breakup Unconformity
Transform Fault

Figure 5

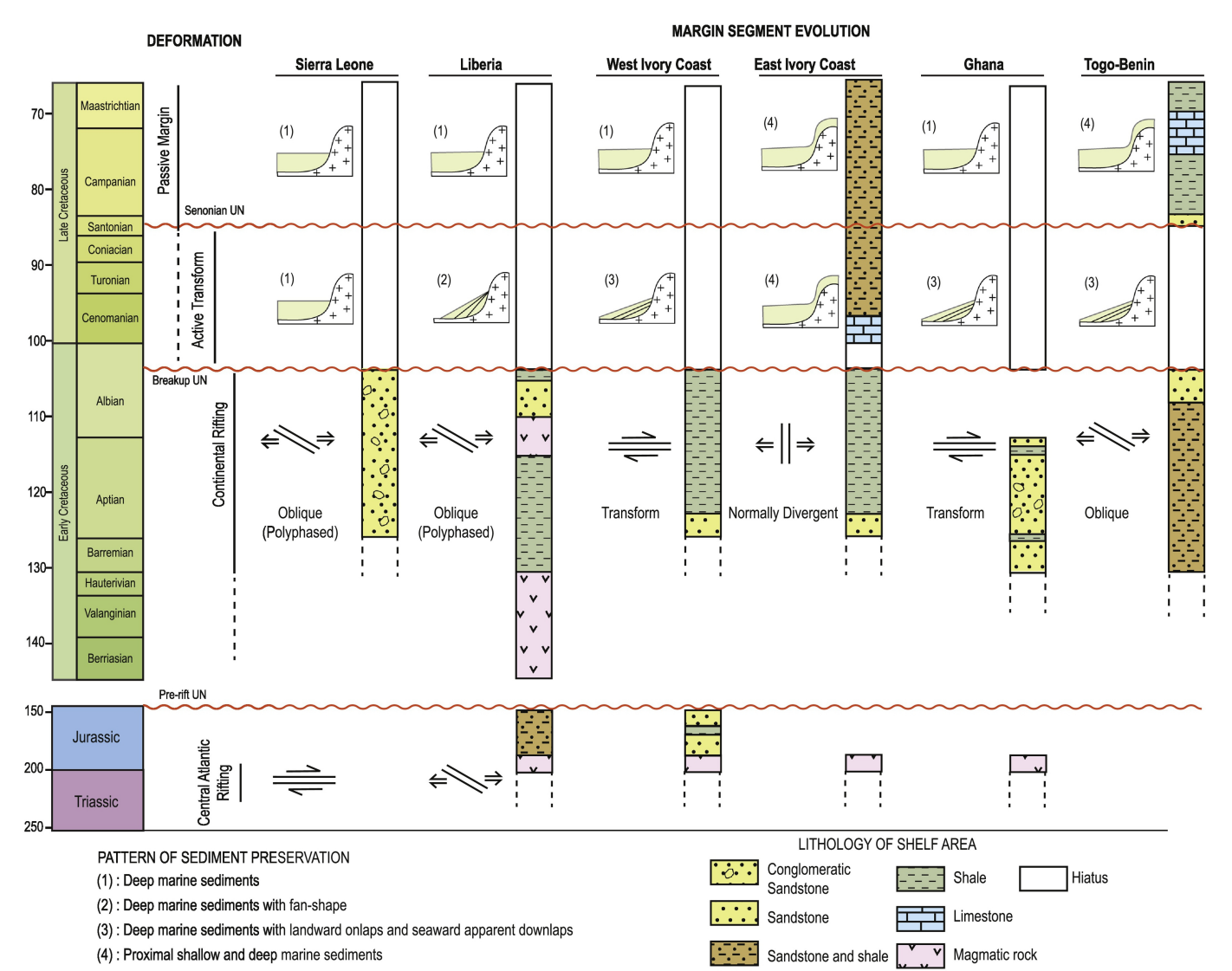
DEFORMATION
MARGIN SEGMENT EVOLUTION
Sierra Leone
Liberia
West Ivory Coast
East Ivory Coast
Ghana
Togo-Benin
Late Cretaceous
Early Cretaceous
Maastrichtian
Campanian
Santonian
Coniacian
Turonian
Cenomanian
Albian
Aptian
Barremian
Hauterivian
Valanginian
Berriasian
Jurassic
Triassic
70
80
90
100
110
120
130
140
150
200
250
Passive Margin
Active Transform
Continental Rifting
Central Atlantic Rifting
Senonian UN
Breakup UN
Pre-rift UN
(1)
(2)
(3)
(4)
Oblique (Polyphased)
Oblique (Polyphased)
Transform
Normally Divergent
Transform
Oblique
PATTERN OF SEDIMENT PRESERVATION
(1) : Deep marine sediments
(2) : Deep marine sediments with fan-shape
(3) : Deep marine sediments with landward onlaps and seaward apparent downlaps
(4) : Proximal shallow and deep marine sediments
LITHOLOGY OF SHELF AREA
Conglomeratic Sandstone
Sandstone
Sandstone and shale
Shale
Limestone
Magmatic rock
Hiatus

Figure 6

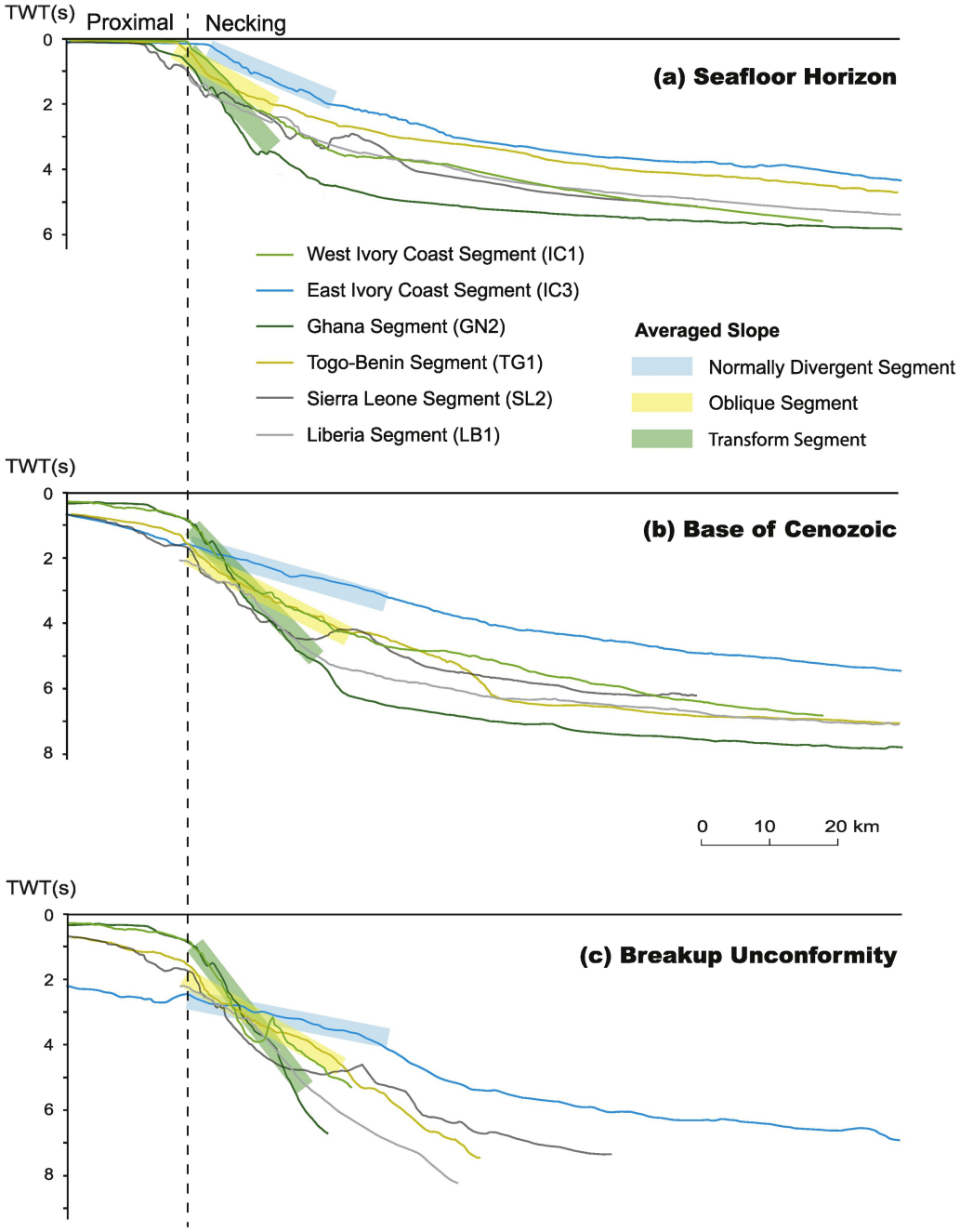
TWT(s)
Proximal
Necking
0
2
4
6
(a) Seafloor Horizon
West Ivory Coast Segment (IC1)
East Ivory Coast Segment (IC3)
Ghana Segment (GN2)
Togo-Benin Segment (TG1)
Sierra Leone Segment (SL2)
Liberia Segment (LB1)
Averaged Slope
Normally Divergent Segment
Oblique Segment
Transform Segment
TWT(s)
0
2
4
6
8
(b) Base of Cenozoic
0
10
20 km
TWT(s)
0
2
4
6
8
(c) Breakup Unconformity

Figure 7

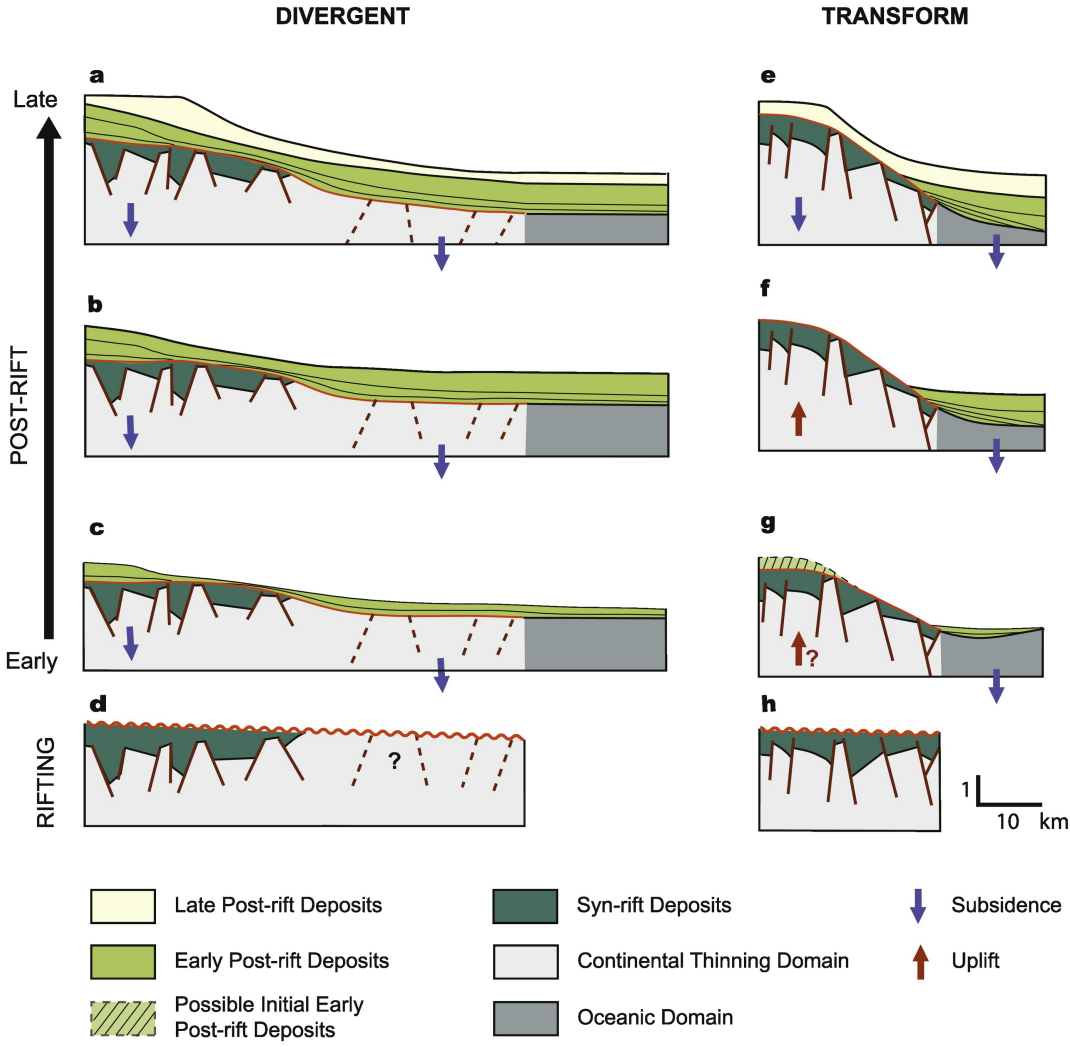
DIVERGENT
TRANSFORM
Late
POST-RIFT
Early
RIFTING
a
b
c
d
e
f
g
h
?
?
1
10 km
Late Post-rift Deposits
Early Post-rift Deposits
Possible Initial Early Post-rift Deposits
Syn-rift Deposits
Continental Thinning Domain
Oceanic Domain
Subsidence
Uplift

Figure 8