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Meta-analysis of the long-term stratigraphic evolution of rifted margin basins: The GeoDyNamilal Analysis approach applied to the South Atlantic Ocean

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Abstract

Models of the formation of rifted margins have significantly evolved over the last decades by identifying new styles of crustal thinning and magmatic production. However, the expression of these different processes in the depositional environments of the overlying basins remains to be determined. Using only published data, we integrated the sedimentary evolution of 21 basins of the Equatorial, Central and South segments of the South Atlantic that record various styles of crustal thinning and magmatic production. To compare these basins that underwent rifting at different times, we developed a new type of analysis allowing to evaluate statistically the (dis)similarities in depositional environment trends by normalizing them to the tectonic phases of the basin (syn-rift, transition and post-rift) rather than the stratigraphic or absolute ages: The GeoDyNamilal Analysis. We show that the timing of the long-term retrograding mega-sequence driven by lithosphere thinning depends on the deformation style and magma production. Along oblique margins of the Equatorial Segment, deepening initiated during syn-rift because their narrow crustal thinning style favours rapid tectonic subsidence surpassing sediment supply. Along wide margins of the Central Segment, deepening is initiated later, at the end of the transition phase, because depth-dependent thinning favours slow tectonic subsidence and late break-up. Along magma-rich margins of the South Segment, deepening is initiated during the transition phase, after volcanics stopped filling accommodation created by subsidence. In the Central Segment, evaporites accumulated during the second half of the transition phase, when crustal thinning ceased in the proximal margin and migrated to its distal part. Immediately before and during evaporites accumulation, sediments recorded continental and coastal depositional environments resulting from the limited thermal subsidence in the proximal margin domain. Evaporite deposition lasted until the initiation of retrograding mega-sequence, at the onset of the post-rift phase and the end of crustal thinning in the distal margin.

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KEYWORDS

crustal necking, rifted margin, sedimentary basin, South Atlantic Ocean, stratigraphic architecture

1 | INTRODUCTION

The stratigraphic architectures of sedimentary basins are unique records of the rifting of continents and the formation of rifted margins. They document the evolution through time of depositional environments that provide insights into the state of crustal and lithospheric thinning reached underneath the basin. In particular, continental rift basins usually record continental and coastal depositional environments in the early stages of crustal thinning that evolve to shelf and deep marine as lithospheric thinning progresses, reaches continental break-up and forms the rifted margin (e.g. Bally & Snelson, 1980; Burchfiel, 1983; Gawthorpe & Leeder, 2000; Prosser, 1993). At first order, this deepening forms a long-term retrograding mega-sequence and is driven by the thinning of the lithosphere and its subsequent thermal re-equilibration (e.g. McKenzie, 1978; Royden & Keen, 1980; Sclater & Christie, 1980; Steckler & Watts, 1978).

Nevertheless, driven by progresses in ultra-deep sub-surface imaging, models of lithospheric thinning and of formation of rifts and rifted margins have significantly evolved over the last decades by including new processes such as magmatism, deformation migration, sequential faulting as well as the proportion of ductile deformation of the lower crust associated with the fragile behaviour of the upper crust (e.g. Chenin et al., 2020; Péron-Pinvidic et al., 2019). The combination of these processes results in various crustal thinning styles (referred to as “necking styles” in this paper) and magmatic production during the formation of the rifts and rifted margins (e.g. weak vs. strong crust and magma rich vs. poor margins; Sapin et al., 2021). It also results in a partitioning of the extensional deformation into distinct structural domains across the rift and rifted margins (proximal, necking and hyperextended domains; e.g. Péron-Pinvidic et al., 2013, 2019). Including these new concepts, Chenin et al. (2020) defined a conceptual framework linking the stratigraphic geometries of sedimentary deposits to the successive rifting stages and structural domains. However, the expression of these various necking styles and magmatic activities in the evolution through time of depositional environments in the associated basins remains to be recognized.

To explore these relationships, we integrate the tectono-stratigraphic evolution of many individual basins at continental scale, in order to overview various

Highlights

- We developed a method to analyze the evolution of depositional environments in sedimentary basins at continental scale.
- In all the studied basins of the South Atlantic, we documented the long-term retrograding mega-sequence driven by the stretching of the lithosphere and its subsequent thermal re-equilibration.
- The relative timing of this retrograding mega-sequence depends on the necking style of the rifted margin: during syn-rift for narrow margins, after emplacement of SDR in magma rich margins and after break-up in wide margins.
- The depositional environments of sediments immediately before, and contemporaneous of, the evaporites were homogeneously continental and coastal at the scale of the Central segment.

types of necking styles and magmatic activity. The South Atlantic Ocean is an ideal system for such an analysis as it is composed of three segments with rifted margins showing very contrasted necking styles and magmatic activity (Figure 1). The rifted margins of the Equatorial Segment (Figure 1), formed by right-lateral shearing between South America and Africa (e.g. Moulin et al., 2010), are generally narrow ($\times 10$ km; “strong type”; e.g. Sapin et al., 2021). In contrast, the rifted margins of the Central Segment (Figure 1) are wide ($\times 100$ km) with a ductilely deformed lower crust (“weak type”; e.g. Sapin et al., 2021). Finally, the rifted margins of the South Segment (Figure 1) show the emplacement of important volumes of volcanics during crustal thinning (“magma-rich type”; e.g. Sapin et al., 2021).

Nonetheless, the South Atlantic rifting propagated northward forming the South, Central to the Equatorial segments successively over the Early Cretaceous (from 145 to 100 Ma; e.g. Heine et al., 2013; Moulin et al., 2010). Therefore, the tectonic stages (rifting, break-up and rifted margin) are not coeval in the basins of the three segments and, at a given stratigraphic age, basins may have reached different stages of crustal thinning depending on their geodynamic setting. To account for this, Doust (2003)

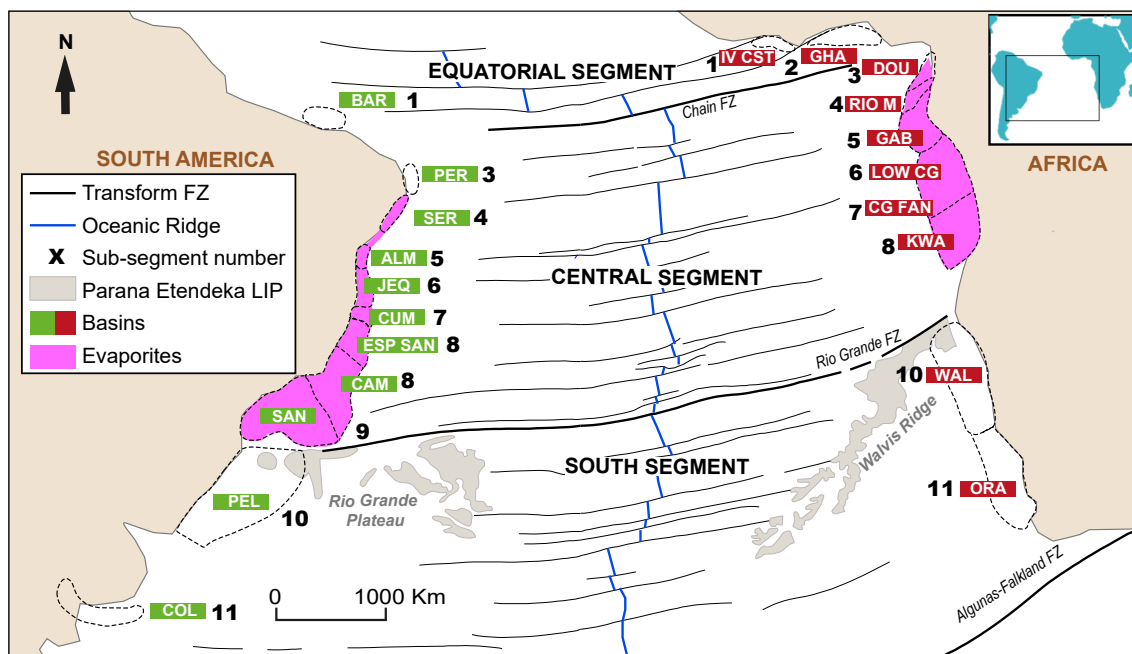


FIGURE 1 Structural map of the South Atlantic showing the 21 studied basins. South American basins are labelled in green and African basins in red. Structural elements after Haghypour (2006). Evaporite deposits are shown in pink after Moulin et al. (2010). Dashed line show basins defined after Beglinger, Doust, et al. (2012a, 2012b) and Coward et al. (1999). For basin labels see Table 1.

developed the “trajectory path” representation that normalizes the evolution of depositional environments in a basin to the tectono-stratigraphic stages (e.g. pre-, syn- and post-rift) rather than the stratigraphic or absolute ages. Using this approach, Beglinger, Corver, et al. (2012) and Beglinger, Doust, et al. (2012a, 2012b) introduced an additional tectono-stratigraphic stage between the syn- and post-rift: the transition stage. They analysed the tectono-stratigraphic histories of the basins of the South Atlantic Central Segment to compare their burial histories and hydrocarbon accumulation potential. To further relate the evolution of depositional environments to the necking styles of rifts and rifted margins, we introduce a new type of analysis: the “GeoDynamical Analysis diagram method” (GeoDNA), building on Doust (2003), Beglinger, Corver, et al. (2012), and Beglinger, Doust, et al. (2012a, 2012b) work. It allows to evaluate statistically the similarities and dissimilarities in the depositional environment trends of basins at continental scale. Using the wealth of published exploration data, we applied this approach to the basins of the Equatorial, Central and South segments of the South Atlantic Ocean. We first present the approach and its application to the South Atlantic basins. We then discuss the implications of our results in terms of variability of long-term stratigraphic trends of sedimentary basins at the scale of the whole South Atlantic and link it with their necking style and magmatic activity (weak vs. strong crust and magma rich vs. poor margins).

2 | METHOD

2.1 | Database

We compile a database for 21 basins along the African and South American rifted margins of the South Atlantic Ocean (Figure 1; Table 1). These basins cover the Equatorial, Central and South segments of the South Atlantic Ocean, respectively, separated by the Chain and Rio Grande transform fault zones (FZ; Moulin et al., 2005; Figure 1). We choose the basins according to the wealth of available published studies that document the stratigraphic architecture of the basins throughout their evolution since initiation of rifting. For the Equatorial segment, we include, two African basins (Ivory Coast: IV CST; Ghana: GHA) and one South American basin (Barreininhas: BAR; Figure 1; Table 1). For the Central segment, we include six African basins (Douala: DOU; Rio Muni: RIO M; Gabon: GAB; Lower Congo: LOW CG; Congo Fan: CG FAN; Kwanza: KWA) and eight South American basins (Pernambuco: PER; Sergipe-Alagoas: SER; Almada-Camamu: ALM; Jequitinhonha: JEQ; Cumuruxatiba: CUM; Espírito Santo: ESP SAN; Campos: CAM; Santos: SAN; Figure 1; Table 1). For the South Segment, we include two African basins (Walvis: WAL; Orange: ORA) and two South American basins (Pelotas: PEL; Colorado: COL; Figure 1; Table 1). We define 11 sub-segments to ease the comparison of basins located on conjugate margins although the basins

TABLE 1 Labels of sub-segments and studied basins located in Figure 1

Segment	Sub-segment	South America		Africa		
Equatorial	1	BAR	Barreirinhas	IV CST	Ivory Coast	
	2			GHA	Ghana	
Central	3	PER	Pernambuco	DOU	Douala	
	4	SER	Sergipe-Alagoas	RIO M	Rio Muni	
	5	ALM	Almada-Camamu	GAB	Gabon	
	6	JEQ	Jequitinhonha	LOW CG	Lower Congo	
	7	CUM	Cumuruxatiba	CG FAN	Congo Fan	
	8		ESP SAN	Espírito Santo	KWA	Kwanza
			CAM	Campos		
South	9	SAN	Santos			
	10	PEL	Pelotas	WAL	Walvis	
	11	COL	Colorado	ORA	Orange	

themselves are not necessarily exactly conjugate (Figure 1; Table 1).

We use 207 published studies to establish the database documenting the evolution of depositional environments through time in each of these basins by compiling geological cross-sections, stratigraphic charts, biostratigraphy data, sedimentary sections or well logs (Table 2). The database includes (i) the stratigraphic and (ii) absolute ages of successive deposits preserved in each basin, including evaporites and volcanics, (iii) the depositional environments of these deposits, (iv) the stratigraphic and (v) absolute ages of the successive rifting phases (syn-rift, transition, post-rift). The rifting phases are defined from the geometry of the corresponding sedimentary deposits following the criteria detailed below (Figure 2). Note that, for the multiphase rifting history of the Colorado basin, we included only data for the rifting phase related to the South Atlantic Ocean in the Early Cretaceous and not for the previous rifting phases (using the definitions of Lovecchio et al., 2018).

In the published studies, the stratigraphic ages are most generally established from biostratigraphy. We calibrated the absolute ages of these biostratigraphic ages using the chart of the International Commission of Stratigraphy of Cohen et al. (2013, updated) and the bio zone synthesis of Chaboureaud et al. (2013). This avoids an artificial variability in absolute ages resulting from the evolution of the reference stratigraphic charts since the study publication. We also harmonize the depositional environments of sedimentary deposits to a reference depositional profile for both clastics and carbonate deposits (Figure 3; Biju-Duval, 2002). Depositional environments are qualitative proxies of depositional depths (i.e. paleo-bathymetries; Figure 3). We attribute numerical values to each depositional system following a proximal (continental = 0) to

distal trend (deep marine = 7). These values allow for comparing statistically the depositional environments from one basin to the other. The strength of our approach is also that, for each item of the database, we also evaluate the variability related to different published interpretations. For example, if different authors propose different depositional environments for given deposits, we incorporated their different hypotheses and estimate the associated variability.

It is important to emphasize that most of the studies available in the literature are restricted to the proximal part of the rifted margins (present-day shelf and upper slope). Despite recent progress in ultra-deep sub-surface imaging, the distal margins are still not well calibrated in terms of sedimentary facies and biostratigraphy. As a consequence, our dataset allows discussing the evolution of depositional environment in the proximal part of the rifted margins, not in their distal part. In terms of crustal geometry, this corresponds to the proximal domain (i.e. where the continental crust is only weakly thinned to ca. 25 km with respect to the onshore cratonic domain ca. 42 km thick) and the beginning of the necking domain (i.e. across which the continental crust is significantly thinned down to ca. 10 km; Péron-Pinvidic et al., 2013; Sutra et al., 2013).

2.2 | Definition of the tectono-stratigraphic stages

To harmonize the attribution of sedimentary deposits to a given rifting phase from one published study to the other, we defined criteria corresponding to the geometry of the deposits in the proximal part of the margin (Figure 2). To avoid circular reasoning, we did not use their facies or depositional environment. Pre-rift sediments (i.e. deposited

TABLE 2 References used for the database

	S. Atl.	Cen. Seg.	Equ. Seg.	S. Seg.	BAR	PER	SER	ALM	JEQ	CUM	ESP SAN	CAM	SAN	PEL	COL	IV CST	GHA	DOU	RIO M	GAB	LOW CG	FAN	KWA	WAL	ORA	
Al-Hajri et al. (2009)		X																							X	
Alvarenga et al. (2016)											X															
Alves et al. (2017)												X														
Anka and Séranne (2004)																					X					
Anka et al. (2009)																					X					
Antobreh et al. (2009)																	X									
Antobreh et al. (2012)																	X									
Aslanian et al. (2009)	X										X									X	X					X
Aslanian and Moulin (2012)													X													
Assumpção et al. (2013)																										
Autin et al. (2013)																										
Baby (2017)																										X
Baby et al. (2018)																										X
Bajolet et al. (2022)																										
Bauer et al. (2000)																										X
Basile et al. (2005)																										
Basile et al. (2013)																										
Bate (1972)																										
Becker et al. (2014)	X																									X
Becker et al. (2016)																										X
Beglinger (2011)	X																									X
Beglinger, Corver, et al. (2012)																										X
Beglinger, Doust, et al. (2012a)																										X
Beglinger, Doust, et al. (2012b)																										X
Beniest (2017)	X																									X
Beniest et al. (2017)	X																									X

TABLE 2 (Continued)

	S. Atl. Seg.	Cen. Seg.	Equ. Seg.	S. Seg.	BAR	PER	SER	ALM	JEQ	CUM	ESP SAN	CAM	SAN	PEL	COL	IV CST	GHA	DOU M	RIO	GAB	LOW CG	CG FAN	KWA	WAL	ORA	
Benkhellil et al. (1995)		X																								
Blaich et al. (2009)	X		X									X	X											X	X	
Blaich et al. (2010)				X							X															
Blaich et al. (2011)	X	X	X								X	X	X									X	X	X	X	
Brandão and Feijó (1994)				X																						
Branner (1890)					X																					
Bray and Lawrence (1999)		X																						X		
Broad et al. (2012)	X																									X
Brognon and Verrier (1966)																						X				
Broucke et al. (2004)																			X							
Brown et al. (1995)																					X					X
Brownfield and Charpentier (2006a)	X																	X	X	X	X	X	X	X	X	
Brownfield and Charpentier (2006b)				X																						
Bueno et al. (2007)																										
Burke and Gunnell (2008)					X																					
Cainelli and Mohriak (1999)																										
de Campo Neto et al. (2007)																										X
Cappelletti et al. (2013)	X																									
Cartwright et al. (2012)	X													X										X	X	
Carvalho et al. (2000)																										X
de Araujo Carvalho et al. (2017)																										
de Castro (1987)																										X
de Castro (1989)						X																				
Chaboureau et al. (2013)	X			X																			X	X	X	

(Continues)

TABLE 2 (Continued)

	S. Atl. Seg.	Cen. Seg.	Equ. Seg.	S. Seg.	BAR	PER	SER	ALM	JEQ	CUM	ESP SAN	CAM	SAN	PEL	COL	IV CST	GHA	DOU M	RIO	GAB	LOW CG	CG FAN	KWA	WAL	ORA	
Chaboureaud et al. (2012)	X																									
Chauvet et al. (2021)				X									X	X										X	X	
Chen et al. (2013)																		X								
Clemente (2013)										X																X
Clemson et al. (1997)																										
Clerc et al. (2018)																		X								
Clift et al. (1997)					X																					
Colli et al. (2014)	X											X	X	X												
Contreras et al. (2010)												X	X	X												
Contreras (2011)												X	X													
Contrucci et al. (2004)		X																			X	X				
Córdoba et al. (2007)						X																				
Coterill et al. (2002)	X	X														X								X		
Coward et al. (1999)	X					X	X	X			X	X	X	X	X			X	X	X	X	X	X	X	X	
Cramez and Jackson (2000)																										X
Dailly et al. (2002)																		X								
Dauteuil et al. (2013)																								X		
Davison (2007)																										
Davison (1999)																										
Davison et al. (2012)												X	X	X	X											
Dehler et al. (2016)				X								X	X	X	X											
Dressel et al. (2015)	X											X	X	X	X									X	X	
Dressel et al. (2017)																								X	X	
Dupré et al. (2007)																			X							
Evain et al. (2015)													X													
Epin et al. (2021)																				X						
Ferreira et al. (2014)																										
Fetter (2009)													X													

TABLE 2 (Continued)

	S. Atl. Seg.	Cen. Seg.	Equ. Seg.	S. Seg.	BAR	PER	SER	ALM	JEQ	CUM	ESP SAN	CAM	SAN	PEL	COL	IV CST	GHA	DOU	RIO	M	GAB	LOW CG	CG FAN	KWA	WAL	ORA	
Figueiredo et al. (2007)		X																									
Filho et al. (2005)										X																	
Florencio et al. (2000)						X																					
França et al. (2007)						X																					
Franke et al. (2007)													X	X													
Freire et al. (2017)										X																	
de Freitas (2006)												X															
Gill and Cameron (2002)																				X							
Gladzenko et al. (1997)																											X
Gladzenko et al. (1998)																											
Goldberg et al. (2017)												X															
Gonçalves (2001)									X																		
Gontijo et al. (2007)										X																	
Greenroyd et al. (2008)																											
Gordon et al. (2013)										X																	
Guillicheau et al. (2011)																											X
Guiraud et al. (1992)																											
Guiraud et al. (2010)																											X
Hadler-Jacobsen et al. (2007)																											
Haghipour (2006)										X																	
Harkin et al. (2020)																											X
Hartley and Allen (1994)																											
Heine et al. (2013)																											
Hudec and Jackson (2002)																											X
Huismans and Beaumont (2011)																											
Jackson et al. (2015)																											X

(Continues)

TABLE 2 (Continued)

	S. Atl. Seg.	Cen. Seg.	Equ. Seg.	S. Seg.	BAR	PER	SER	ALM	JEQ	CUM	ESP SAN	CAM SAN	PEL COL	IV CST	GHA	DOU M	RIO	GAB	LOW CG	CG FAN	KWA	WAL	ORA		
Jackson et al. (2000)	X																								
Jeannot and Buitier (2018)		X																							
Karner et al. (2003)		X																							
Karner and Gamba (2007)	X																								
Karner et al. (1992)				X																					
Karner et al. (1997)																X									
Kollenz et al. (2017)			X										X												X
Kress et al. (2021)												X	X												
Krob et al. (2020)	X																								
Kuchle et al. (2011)								X																	
Kuhlmann et al. (2010)																									
Kukla et al. (2018)	X																								X
Kusznir et al. (2018)			X																						
Lavier et al. (2001)																			X						
Lawrence et al. (2017)															X										
Lentini et al. (2010)	X																								
Lehner and de Rutter (1977)	X																								
Leturmy (2003)																			X						
Loegering et al. (2013)													X												
Loureiro et al. (2018)									X																
Lovecchio et al. (2018)				X																					
Lovecchio et al. (2020)			X																						
Loparev et al. (2021)				X																					
Lucazeau (2003)																			X						
Luzzi-Arbouille et al. (2009)																									
Marcano et al. (2013)													X												X

TABLE 2 (Continued)

	S. Atl.	Cen. Seg.	Equ. Seg.	S. Seg.	BAR	PER	SER	ALM	JEQ	CUM	ESP SAN	CAM SAN	PEL COL	IV CST	GHA	DOU M	RIO	GAB	LOW CG	CG FAN	KWA	WAL	ORA		
Marzoli et al. (1999)																								X	
Maslanyj et al. (1992)	X																								
de Matos (1992)		X																							
de Matos (1999)	X																								
de Matos et al. (2021)	X																								
Maurin and Guiraud (1993)	X	X																							
Maysrenko et al. (2013)				X																					X
Mbina Mounquengui and Guiraud (2009)																	X								
McDermott et al. (2015)																									X
McMillan (2003)																									X
Meyers et al. (1996)																									X
Michels et al. (2018)										X															
Milani et al. (2007)	X				X	X	X	X	X	X	X	X	X	X											
Mills et al. (2017)	X																								
Modica and Brush (2004)																									X
Mohriak et al. (2002)	X																								
Mohriak, Brown, et al. (2008)	X																								
Mohriak, Szatmari, et al. (2012)	X																								
Mohriak, Hobbs, et al. (1990)																									X
Mohriak, Mello, et al. (1990)																									X
Mohriak et al. (1998)																									X
Mohriak and Fainstein (2012)				X																					
Mohriak and Rosendahl (2003)				X																					
Moulin (2003)	X																								

(Continues)

TABLE 2 (Continued)

	S. Atl. Seg.	Cen. Seg.	Equ. Seg.	S. Seg.	BAR	PER	SER	ALM	JEQ	CUM	ESP SAN	CAM	SAN	PEL	COL	IV CST	GHA	DOU M	RIO M	GAB	LOW CG	CG FAN	KWA	WAL	ORA
Moulin et al. (2010)	X	X																		X					
Museur et al. (2020)		X																							
Nemčok et al. (2013)			X																						
Nicolai et al. (2013)																							X		
Norton et al. (2016)	X																								
Ntamak-Nida et al. (2008)												X	X	X	X			X	X						
Ntamak-Nida et al. (2010)																		X	X						
Ojeda (1982)					X	X	X	X	X	X	X	X	X	X	X										
Owona Angue et al. (2011)																		X	X						
Pautot et al. (1973)	X															X									
Pérez-Díaz and Eagles (2017)	X																								
Pérez-Gussinyé et al. (2009)		X																							
Péron-Pinvidic et al. (2013)	X																								
Péron-Pinvidic et al. (2017)																				X					
Peyve (2010)																									
Piedade and Alves (2017)											X														
Pinheiro et al. (2018)																									
Planert et al. (2017)																								X	
Quirk et al. (2013)	X																								
Rangel et al. (2007)																									
Renne et al. (1992)	X																								
Rodovalho et al. (2007)																									
Rohais et al. (2021)																									
Rohde et al. (2013)																								X	
Rosendahl and Groschel-Becker (1999)																									
Routby et al. (2009)																								X	X

TABLE 2 (Continued)

	S. Atl. Seg.	Cen. Equ. Seg.	S. Seg.	BAR	PER	SER	ALM	JEQ	CUM	ESP SAN	CAM	SAN	PEL	COL	IV CST	GHA	DOU	RIO M	GAB	LOW CG	CG FAN	KWA	WAL	ORA	
Sabato Ceraldi et al. (2017)		X																							
Saller et al. (2016)																									X
Sapin et al. (2016)			X																						
dos Scherer et al. (2014)																									
Schmidt (2004)			X																						X
Séranne et al. (1992)																			X						
Séranne and Anka (2005)																				X				X	X
Serité et al. (2017)																									X
Strozyk et al. (2017)														X											
Tankard et al. (2012)		X																							
Thompson et al. (2015)		X																							
Torsvik et al. (2009)		X																							
Trosdfort Jr. et al. (2007)																									X
Turner et al. (2003)																									X
Turner (1999)																									
Untermeier et al. (2010)		X																							
Valle et al. (2001)																									X
Vera et al. (2010)																									
Winter et al. (2007)																									
Wilson et al. (2003)										X															
Ye et al. (2017)																									X
Ye et al. (2019)																									X
Zalán and Matsuda (2007)																									X

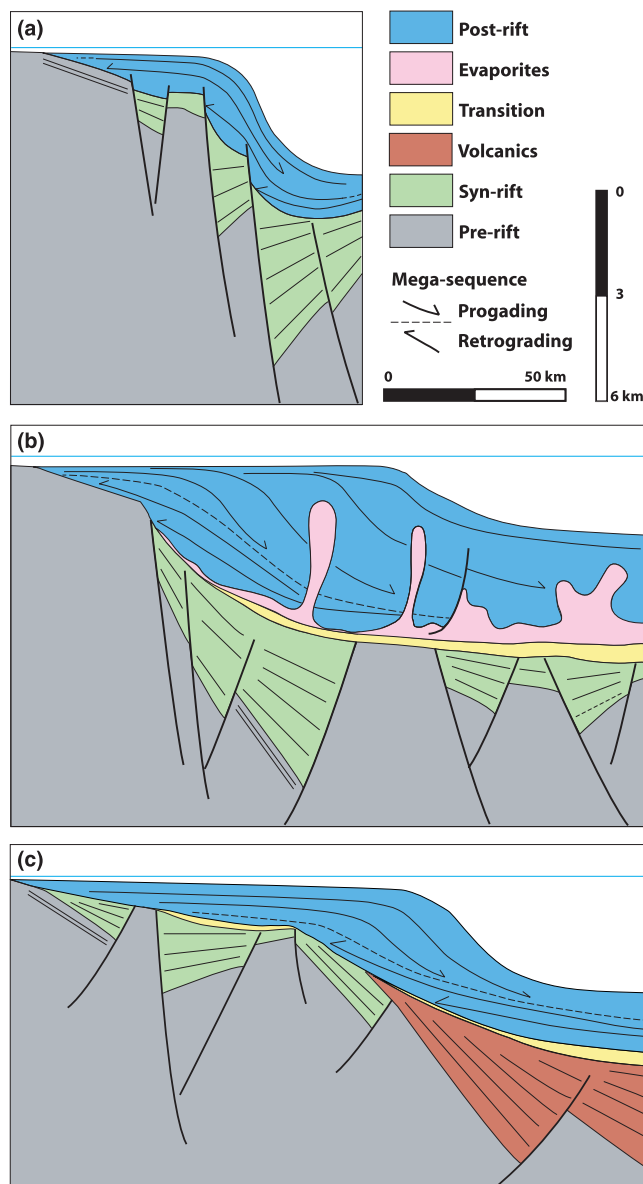


FIGURE 2 Schematic cross-sections illustrating the definition of the tectono-stratigraphic stages in the proximal part of (a) the narrow oblique margins of the equatorial segment, (b) the wide margins of the central segment and (c) the volcanic margins of the south segment.

before crustal thinning) correspond to deposits deformed by the rift structures (i.e. mostly tilted by faults) without growth structure (Figure 2). Syn-rift deposits (i.e. coeval of crustal thinning in the proximal domain) are deformed by crustal thinning structures (i.e. mostly tilted blocks) and show growth structures (i.e. mostly fans; Figure 2). The basins of the Central and South segments show “transition” deposits between the syn-rift and the post-rift sedimentary wedges (Figure 2b,c). Transition deposits are sub-horizontal, bounded by unconformities, with little or no effect on the underlying rift structures. In this work, we consider that these deposits correspond to the sediments

sealing syn-rift structures when crustal thinning migrated from the proximal to the distal parts of the margin (e.g. Blaich et al., 2011) and/or was accommodated by lower crust deformation (e.g. Driscoll & Karner, 1998; Karner et al., 2003; Karner & Gambôa, 2007). Above, post-rift deposits first onlap transition or syn-rift deposits (retrograding mega-sequence) and then, in some basins, show downlaps (prograding mega-sequence; Figure 2).

2.3 | Construction of trajectory paths

Following Doust (2003), Beglinger, Corver, et al. (2012) and Beglinger, Doust, et al. (2012a, 2012b), for every rifting stage (syn-rift, transition, post-rift), we plotted the range of depositional environments recorded by the sediments in the proximal part of the margin proposed in published studies (from the most proximal to most distal facies, i.e. the shallowest to the deepest settings; Figure 4). We expanded on Doust (2003) method by dividing the stages in 10 steps of equal duration (e.g. 10% of the stage duration) and by including the various interpretations proposed by the different authors, the graphical mean (medoid) and the relative timing of emplacement of evaporites and volcanics (Figure 4a).

2.4 | GeoDynamical Analysis (GeoDNA) diagrams

We further expand on the method of Doust (2003) method by representing the evolution of depositional environment in the basins at continental scale. For each rifting stage of each basin, we use box-plots and means to represent the variability and the average of depositional environments (Figure 5). As we categorized the depositional environments with alpha-numerical values (Figure 3), we can use statistical tests to assess and compare objectively the spatio-temporal evolution of the depositional environments, whether within each segment or along the South Atlantic rifted margins.

We used non-parametric statistical tests on the alpha-numeric depositional environment values (extended Mood's median test and pairwise Median Test; Brown & Mood, 1951; Hothorn et al., 2008) and their variability (variance Levene's test; Levene, 1960). We used R (R Core Team, 2021) and the packages *stats* (R Core Team, 2021), *RVAideMemoire* (Hervé, 2021), *coin* (Hothorn et al., 2008) and *car* (Fox & Weisberg, 2019), respectively, to perform those tests. The extended Mood's median test evaluates if the median depositional environments of the compared segments are equal (p -value $>.05$) or significantly different (p -value $<.05$). The Levene's test focuses on the homogeneity of variance

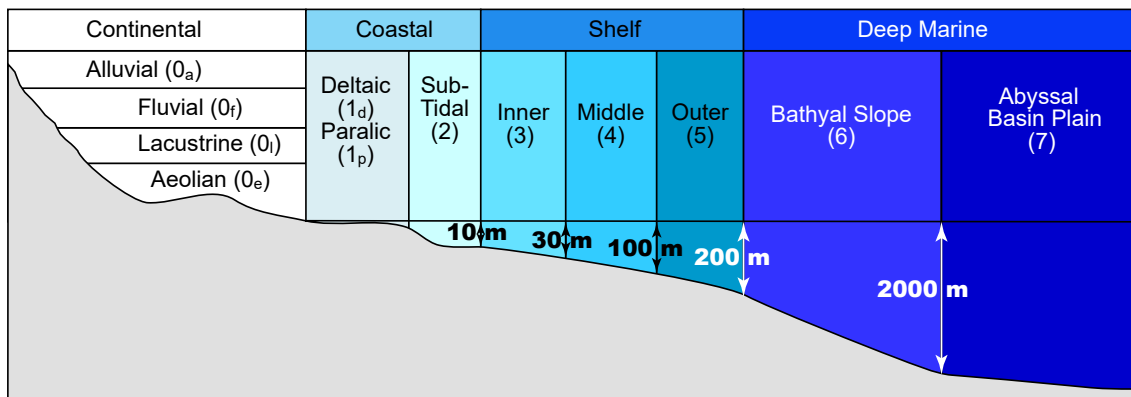


FIGURE 3 Synthetic depositional profile for clastics and carbonates deposits (and associated alpha-numerical values: 0 to 7).

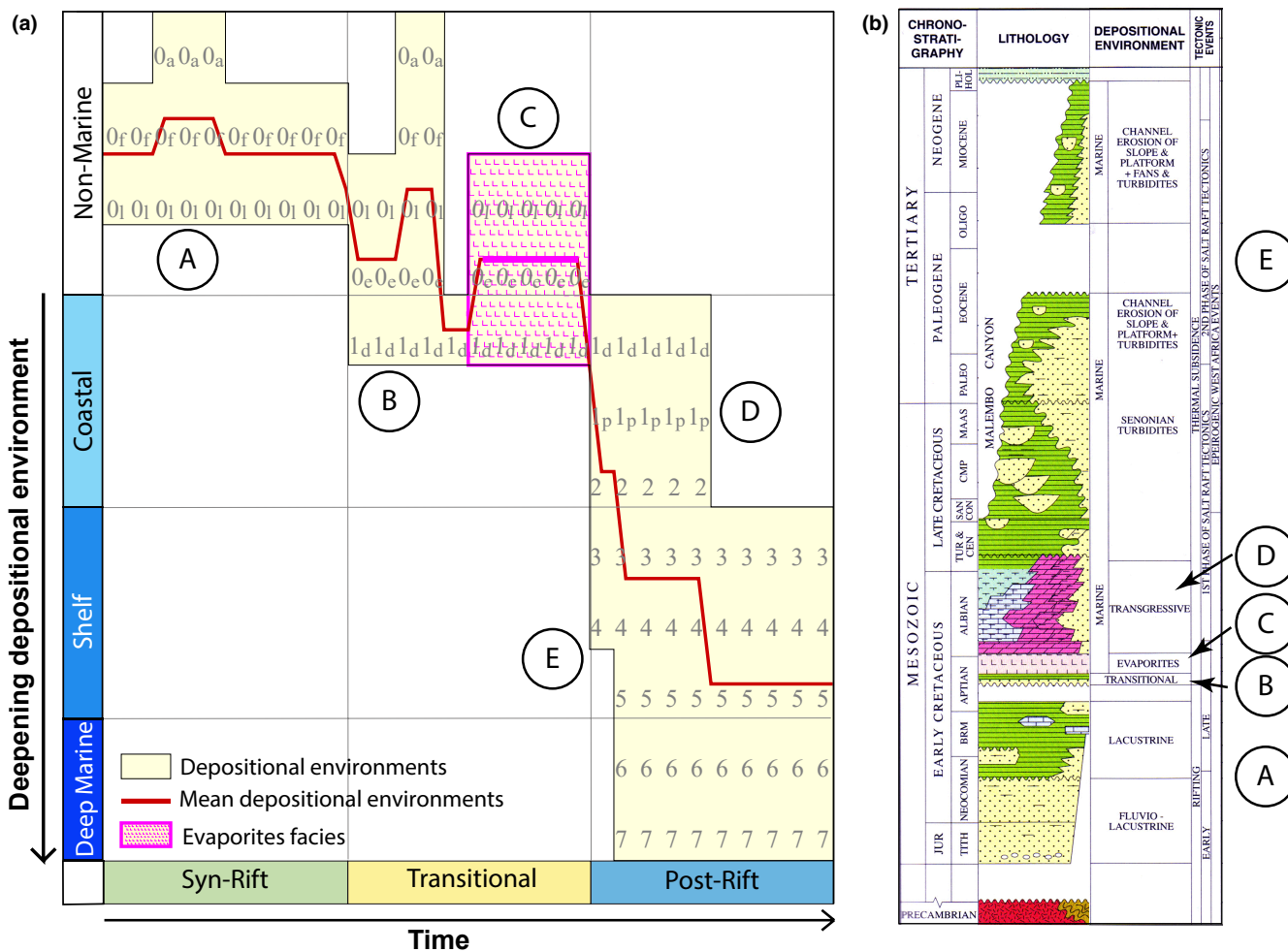


FIGURE 4 (a) Example of the trajectory path for the lower Congo basin showing the depositional environments (alpha-numerical values of depositional environments defined in Figure 3; range: Yellow box; mean: Red line) in the proximal domain of the margin normalized to rifting stages (build using Beglinger, Corver, et al., 2012, Beglinger, Doust, et al., 2012b; Chaboureaud et al., 2013; Coward et al., 1999; Séranne et al., 1992; Valle et al., 2001; see Table 2). Timing of evaporite deposition is highlighted in pink. (b) Example of one of the stratigraphic charts used to establish the trajectory path (modified after Coward et al., 1999) with labels relating to panel (a).

between two segments. A *p*-value higher than .05 indicates that the compared segments record the same variability of depositional environments, while a *p*-value lower than .05 indicates the opposite. Thus, the lower the *p*-value, the more robust the comparison.

3 | THE SOUTH AND EQUATORIAL ATLANTIC OCEANS

The South Atlantic Ocean, propagated northward, forming the South, Central and Equatorial segments, over

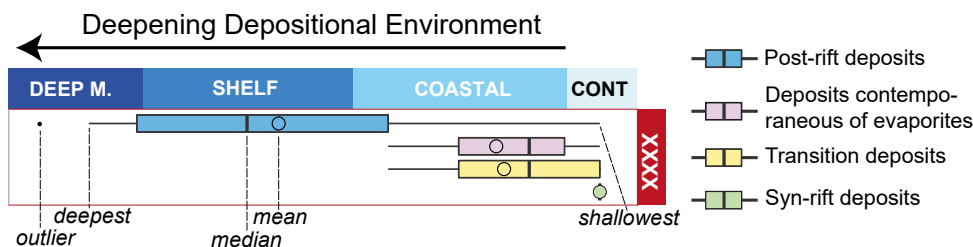


FIGURE 5 Example of a GeodNA diagram for a basin showing the distribution of depositional environments of sedimentary deposits during each tectono-stratigraphic stages: Syn-rift in green, transition in yellow, deposits contemporaneous of evaporites in pink and post-rift in blue. The box-plots represent the variability in the depositional environment values: The median (i.e. the middle value of the environments variability), the first (Q_1) and third (Q_3) quartiles (bounding 50% of the possible depositional environments), the range of values from the minimum (shallowest) to the maximum (deepest) depositional environments (values within the 1.5 interquartile range ($IQR = Q_3 - Q_1$) below Q_1 or above Q_3), and the identification of abnormal depositional environment values (outliers) when present (values below or above the minimal and maximal values).

several tens of Myr, from the Late Jurassic (ca. 150 Ma) to the Albian (ca. 100 Ma; Benkhelil et al., 1995; Brandão & Feijó, 1994; Davison, 1999; Figueiredo et al., 2007; Heine et al., 2013; Lovecchio et al., 2020; Moulin et al., 2010; Torsvik et al., 2009; Zalán & Matsuda, 2007).

3.1 | Crustal structure of South Atlantic rifted margins

The crustal structure of the rifted margins varies along the strike of the South Atlantic Ocean. In particular, the width of the margin segments, corresponding to the distance over which most of the crustal thinning is accommodated (necking and distal domains; Péron-Pinvidic et al., 2013; Sutra et al., 2013), varies between the Equatorial, Central and South segments.

The rifted margins of the Equatorial Segment (Figure 1) are generally narrow (20–100 km; Jeannot & Buitter, 2018; Loparev et al., 2021; Montenegro et al., 2021; Sapin et al., 2016; Ye et al., 2019; Figure 2a). This is related to the fact that the Equatorial Atlantic rift was formed at high obliquity by right-lateral shearing between South America and Africa (e.g. Basile et al., 2005; de Matos, 1992, 2000; Guiraud et al., 1992; Moulin et al., 2010).

In contrast, the rifted margins of the Central Segment (Figure 1) are wide (up to 600 km; Clerc et al., 2018; Contrucci et al., 2004; de Matos et al., 2021; Evain et al., 2015; Mohriak, Nemčok, et al., 2008; Moulin, 2003; Moulin et al., 2005; Péron-Pinvidic et al., 2013, 2017; Pinheiro et al., 2018; Unternehr et al., 2010; Figure 2b). Their crustal necking domains are associated with wide distal hyperextended domains and ductilely deformed lower crust (“weak or hot margin type”; e.g. Clerc et al., 2018; Epin et al., 2021; Loureiro et al., 2018; Péron-Pinvidic et al., 2013; Unternehr et al., 2010).

The rifted margins of the South segment (Figure 1) show important volumes of volcanics forming “seaward dipping reflectors” (SDR; e.g. Bauer et al., 2000; Blaich et al., 2009; Chauvet et al., 2021; Clemson et al., 1997; Franke et al., 2007; Gladchenko et al., 1997; McDermott et al., 2015; Stica et al., 2014; Figure 2c). These magmatic rifted margins are fairly wide (>200 km) with SDR emplaced in the rift-related structures (Bauer et al., 2000; Chauvet et al., 2021; Franke et al., 2007; Gladchenko et al., 1997; McDermott et al., 2015; Stica et al., 2014). Additionally, the lower crust is associated with underplating traditionally interpreted as magmatic additions (Bauer et al., 2000; Becker et al., 2014, 2016; Gladchenko et al., 1998; McDermott et al., 2015).

3.2 | Stratigraphic architecture of the South Atlantic rifted margin basins

In the proximal parts of the rifted margins of the South Atlantic, syn-rift deposits are mainly preserved within tilted blocks (Figure 2). They recorded mostly continental depositional environments (alluvial fan, fluvial, lacustrine; Beglinger, Corver, et al., 2012; Beglinger, Doust, et al., 2012a; Cainelli & Mohriak, 1999 and references therein). In the Equatorial Segment basins, the continental shales and sandstones were covered by shallow marine deposits further deepening until break-up in the Albian (e.g. Brownfield & Charpentier, 2006a; Córdoba et al., 2007; Trosdorf Jr. et al., 2007).

The basins of the Central and South Segment show “transition” deposits, between the syn-rift and the post-rift sedimentary wedges (Figure 2b,c). These sub-horizontal clastic deposits are bounded by unconformities and record continental/lacustrine or shallow marine depositional environments (often referred to as “pre-salt sag basin”; Blaich et al., 2011; Clemson et al., 1997; Jackson

et al., 2000; Karner et al., 2003; Karner & Gambôa, 2007; Lentini et al., 2010; Mohriak, Nemčok, et al., 2008; Moulin et al., 2005; Unternehr et al., 2010). They form a long wavelength “flexural” basin (several hundreds of km wide and several kms thick), with little or no effect of the underlying rift structures (e.g. Jackson et al., 2000; Karner et al., 2003; Karner & Gambôa, 2007; Lentini et al., 2010; Mohriak, Nemčok, et al., 2008; Moulin et al., 2005). Depending on which of the bounding unconformities is interpreted as the break-up uniformity, the geodynamical stage during which these deposits are formed is debated in the literature: either before continental break-up (e.g. Beglinger, Corver, et al., 2012; Beglinger, Doust, et al., 2012a; Chaboureau et al., 2013; Karner et al., 1997, 2003; Karner & Gambôa, 2007; Unternehr et al., 2010) or immediately after continental break-up (e.g. Jackson et al., 2000). As mentioned above, in this work, we consider that the transition deposits seal syn-rift structures in the proximal part of the margin, when crustal thinning migrate from the proximal to the distal parts of the margin (e.g. Blaich et al., 2011) and/or is accommodated by lower crust deformation (e.g. Driscoll & Karner, 1998; Karner et al., 2003; Karner & Gambôa, 2007).

The Central Segment basins include evaporitic deposits in the upper part of the transition packages (e.g. Brognon & Verrier, 1966; Lehner & de Ruyter, 1977; Mohriak, Mello, et al., 1990; Ojeda, 1982; Pautot et al., 1973; Figure 2b). They have been deposited, at the scale of the Central Segment, within few Myrs in the Aptian (e.g. Chaboureau et al., 2013 and references therein). The present-day thickness of the evaporitic deposits is highly variable due to salt flow: it reaches 5 km in the diapirs of distal margins (e.g. Cramez & Jackson, 2000; Marton et al., 2000; Mohriak, Mello, et al., 2012) although their original thickness may have only be about 1 to 3 km (e.g. Davison et al., 2012). In any case, this evaporite basin falls within the range of “salt giant basin” thickness (Van den Belt & de Boer, 2007).

The stratigraphic architecture of the post-rift phase deposits varies significantly from one basin to another. In the Equatorial Segment basins, the post-rift sedimentary systems remained under open marine depositional environments modulated by eustatic variations, with various proportions of carbonates and expressions of unconformities from one basin to the other (e.g. Brownfield & Charpentier, 2006a; Córdoba et al., 2007; MacGregor et al., 2003; Trostdorf Jr. et al., 2007). In the Central Segment, the post-rift stratigraphic architecture above the evaporites first recorded marine depositional environments associated with carbonates (e.g. Beglinger, Corver, et al., 2012; Beglinger, Doust, et al., 2012a; Coward et al., 1999; Milani et al., 2007). This suggests a low terrigenous input to the rifted margins at the time (Séranne & Anka, 2005). These carbonates were mostly deposited

in the Albian although they lasted to the Cenomanian or the Coniacian in the northern part of the South American rifted margin (e.g. Beglinger, Corver, et al., 2012; Beglinger, Doust, et al., 2012a; Coward et al., 1999). From the Cenomano-Turonian onward, the deepening to open marine clastic depositional environments dominated (i.e. the retrograding mega-sequence; Beglinger, Corver, et al., 2012; Beglinger, Doust, et al., 2012a; Coward et al., 1999; MacGregor, 2013; Milani et al., 2007; Séranne & Anka, 2005). Nonetheless, some basins then underwent a prograding mega-sequence initiating at various times in the Cenozoic (e.g. Eocene in Sergipe-Alagoas basin, Oligocene in Campos basin and Gabon basin, etc...) with clastic prograding wedges and associated distal turbidite deep-sea fans located at the outlet of the main sediment routing systems draining the continents (e.g. Anka & Séranne, 2004; MacGregor, 2013; Milani et al., 2007; Séranne et al., 1992). These were usually associated with massive sedimentary supply as indicated by the increase in accumulation rates (e.g. Lavier et al., 2001; Leturmy, 2003; MacGregor, 2013). In the South Segment, the post-rift stratigraphic architecture also showed shallow marine carbonates (Aptian to Turonian) followed by an aggrading/retrograding sequence under open marine environments (Baby et al., 2018; Bueno et al., 2007; Coward et al., 1999; Kress et al., 2021; Séranne & Anka, 2005). Along the African rifted margin, it was followed by diachronous clastic prograding sequences associated with distal turbidite deep-sea fans located at the outlet of the main sediment routing systems (e.g. Late Cretaceous in Orange basin and Cenozoic in Walvis basin; Baby et al., 2018; MacGregor, 2013; Séranne & Anka, 2005).

4 | RESULTS

4.1 | Temporal evolution of depositional environments in each segment of the South Atlantic Ocean

4.1.1 | Equatorial Segment

The trajectory path of the studied basins in the Equatorial Segment show that deposits recorded continental depositional environments during the first half of the syn-rift phase (Figure 6; Table S1). Then, during the second half of the syn-rift phase, two out of three basins (i.e. except the GHA-2 basin) recorded a deepening to coastal environments signing the beginning of the retrograding mega-sequence. The studied basins recorded neither transition and evaporitic deposits. During the first half of the post-rift phase, the basins recorded further deepening to shelf and deep marine depositional environments (i.e. ongoing

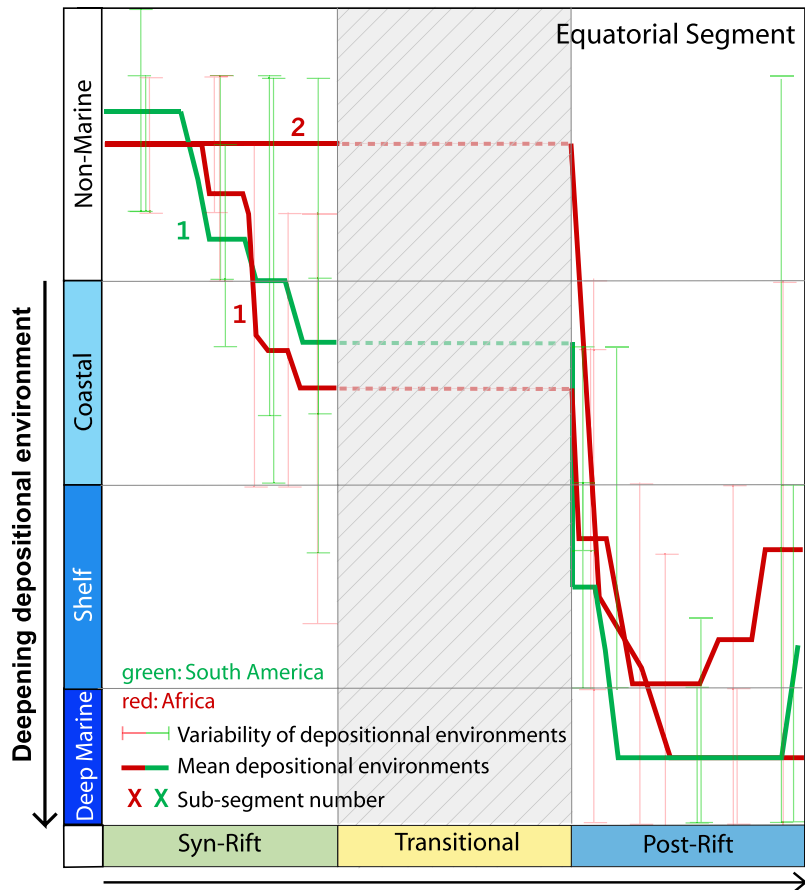


FIGURE 6 Trajectory paths for the three basins of the equatorial segment (see locations in Figure 1). The dashed are correspond to the transition phase, not recorded along this segment.

retrograding mega-sequence). During the second part of the post-rift phase, two out of three basins (i.e. except the IV CST-1 basin) recorded a shallowing to shelf environments (i.e. a prograding mega-sequence).

4.1.2 | Central Segment

Note that, in the results below, we use only our database and not the previously published trajectory paths (e.g. Beglinger, Corver, et al., 2012; Beglinger, Doust, et al., 2012a, 2012b). During the syn-rift and transition phases, the trajectory paths of the basins of the Central Segment show mostly continental depositional environments and some coastal deposits (Figure 7; Table S1). Evaporites were deposited only during the second half of the transition phase (Figure 7). Sediments immediately underlying or contemporaneous with the evaporites recorded continental and coastal depositional environments. The passage between transition and post-rift was associated with a sharp deepening of the depositional environments to shelf and deep marine (Figure 7). The retrograding mega-sequence thus occurred at a different stage than in the Equatorial Segment basins, that is to say after break-up instead of during syn-rift (Figures 6 and 7). Accordingly, the sediments immediately overlying the

evaporites recorded shelf and deep marine depositional environments (Figure 7). After the retrograding mega-sequence, during the late post-rift, several basins recorded a shallowing trend (prograding mega-sequence) to shelf and coastal depositional environments (i.e. except RIO M-4, LOW CG-6, CG FAN-7, SAN-9; Figure 7c,f,g).

4.1.3 | South Segment

In the South Segment, syn-rift deposits included volcanics in addition to clastic sediments in three out of four studied basins (i.e. except the COL-11 basin; Figure 8; Table S1). Volcanics emplaced during the first half of the transition phase (Figure 8). They stopped earlier in African basins (WAL-10 and ORA-11) than in the South American basins (PEL-10 and COL-11; Figure 8). The end of their emplacement was followed by a deepening of depositional environments to coastal and shelf facies (i.e. retrograding mega-sequence). The retrograding mega-sequence thus occurred before break-up, as the difference with the Central segment basins (Figures 7 and 8). The post-rift phase recorded shelf and deep-marine depositional facies (Figure 8). After the end of the retrograding mega-sequence, the basins of the South Segment recorded a retrograding mega-sequence at various stages of the post-rift phase (Figure 8).

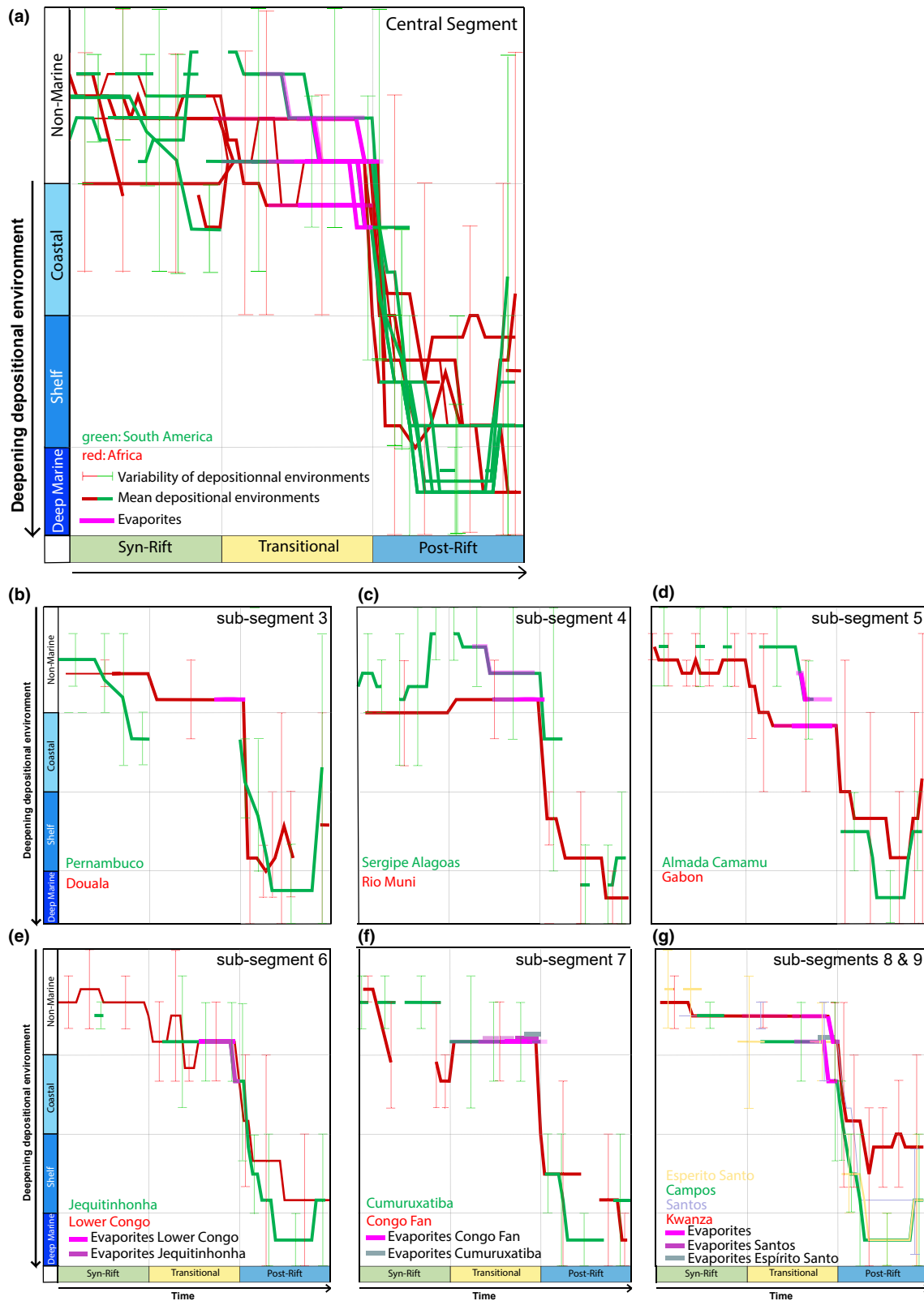


FIGURE 7 (a) Trajectory paths for the 13 basins of the central segment (see locations in Figure 1). (b) Sub-segment 3: PER-DOU; (c) sub-segment 4: SER-RIO M basins; (d) sub-segment 5: ALM- GAB basins; (e) sub-segment 6: JEQ-LOW CG basins; (f) sub-segment 7: CUM-CG FAN basins and (g) sub-segments 8 and 9: ESP/CAM/SAN- KWA basins.

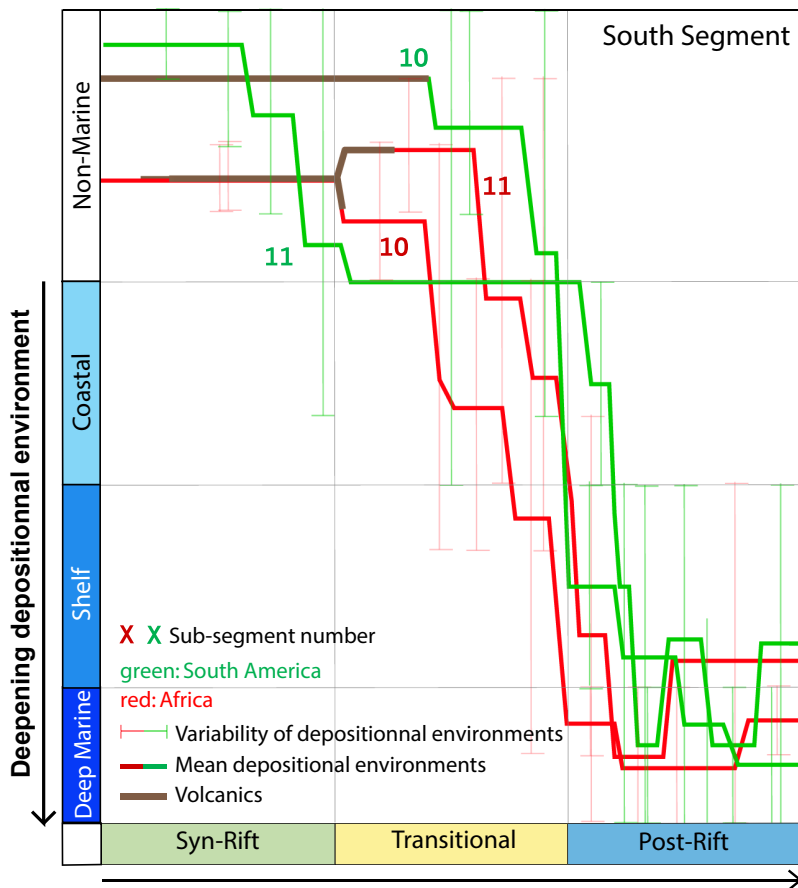


FIGURE 8 Trajectory paths for the four basins of the south segment (see location on Figure 1).

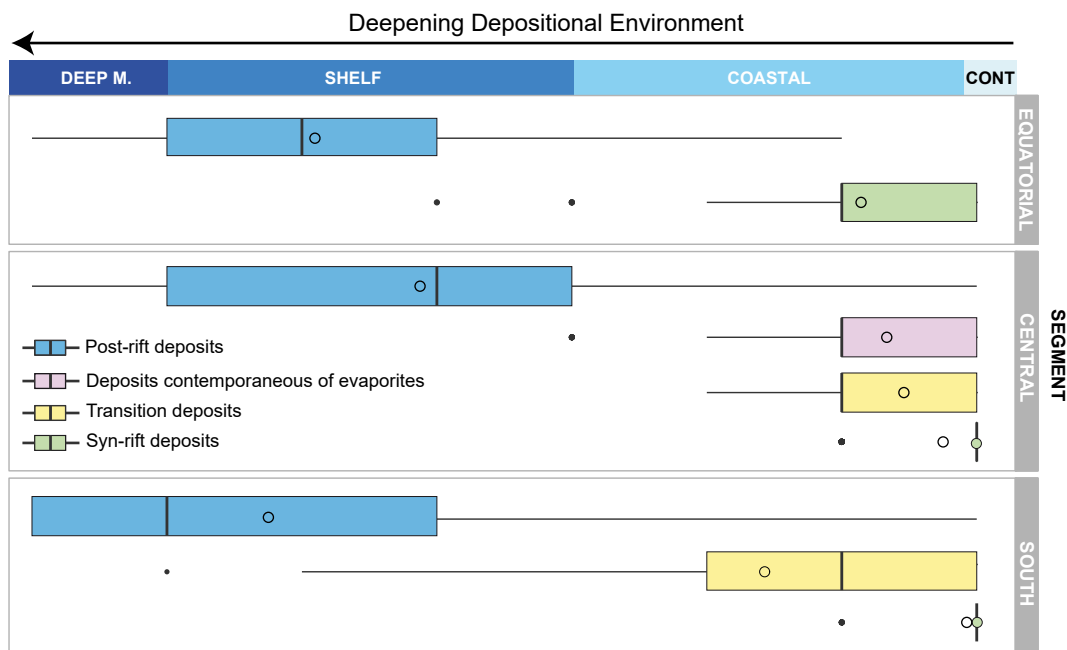


FIGURE 9 GeodNA of all basins in each segment of the South Atlantic Ocean margins (African and South American).

4.2 | Evolution of depositional environments at the scale of the South Atlantic Ocean

We established the GeodNA diagram of basins within each South Atlantic segment (Figure 9) and the GeodNA

diagrams of each basin from North to South on each conjugated margin (Figures 10 and 11). Using the alpha-numeric values assigned to each depositional environment (Figure 3), we also tested the similarities of depositional environments within the basins of each segment (Figure 12a), between the basins of each segment

conjugate margins of (Figure 12b) and between the basins of each segment of each conjugate margin (Figure 12c). In each comparison, we used the extended Mood's test complemented by its pairwise version to compare the averaged depositional environments from one segment to the other and the Levene's variance test to compare their variability.

As expected, during syn-rift, the basins of the South Atlantic predominantly recorded continental environments

(Figure 9; e.g. Gawthorpe & Leeder, 2000; Prosser, 1993). Nevertheless, the basins of Equatorial segment included coastal depositional environment as well (i.e. IV CST, BAR; Figures 9–11a) as they underwent deepening during the syn-rift phase (Figure 6). Accordingly, at the scale of segments, the depositional environments of the Equatorial segment basins are statistically significantly different than the other segments (black ovals in Figure 12a,c).

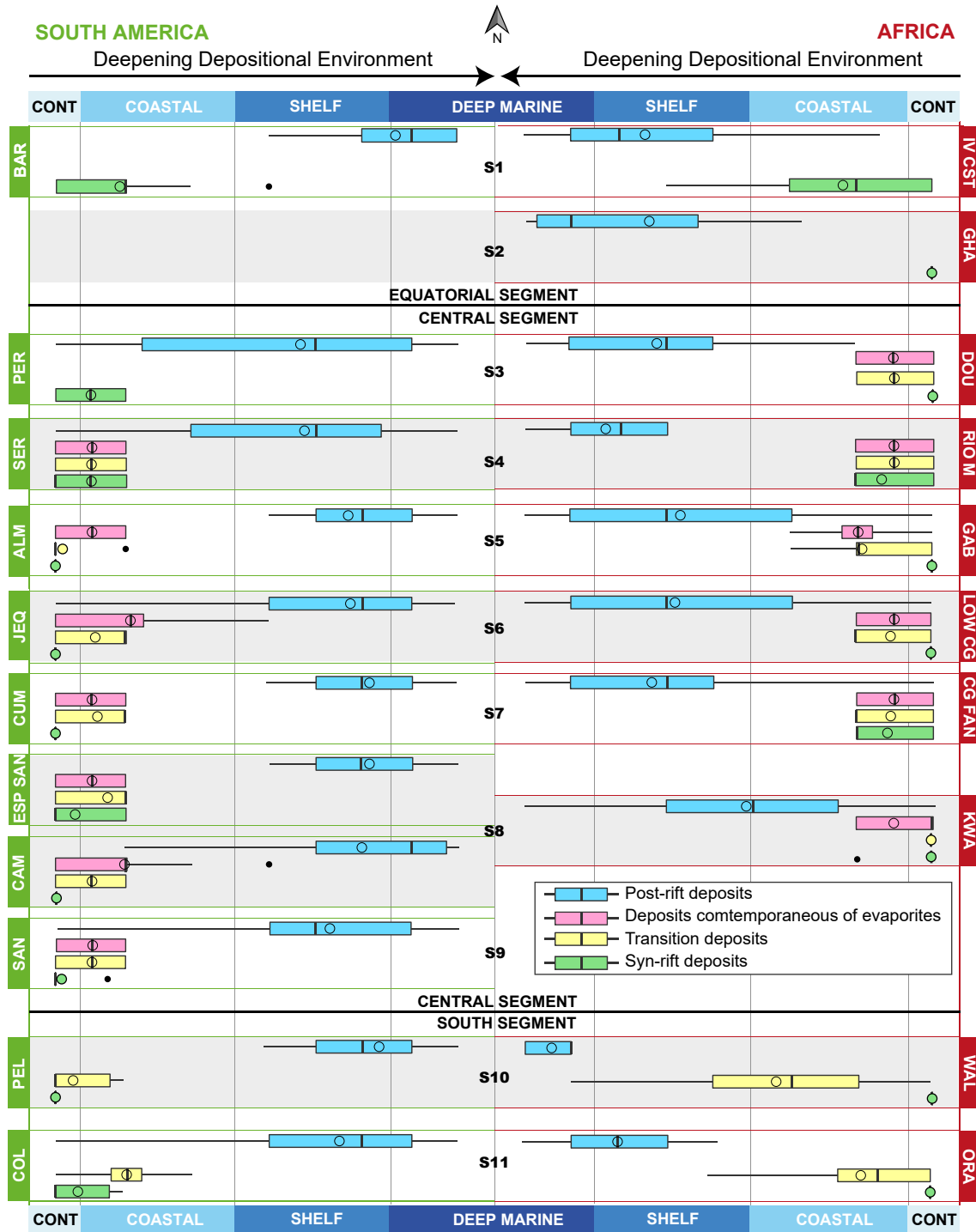


FIGURE 10 GeodNA of the basins of the South Atlantic conjugate margins organized from north to south. Sub-segments are highlighted in grey or white and numbers are shown in black.

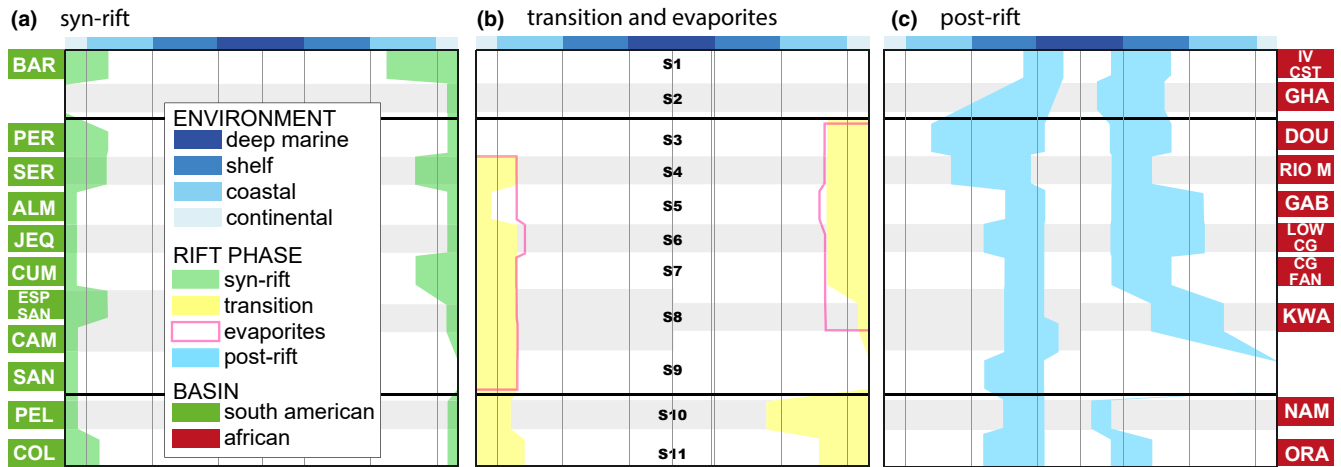


FIGURE 11 Simplified GeoDNA diagram of the basins of the South Atlantic Ocean highlighting facies variability during the: (a) syn-rift phase, (b) transition phase and evaporites and (c) post-rift phase. Sub-segments are highlighted in white and grey and numbers are shown in black.

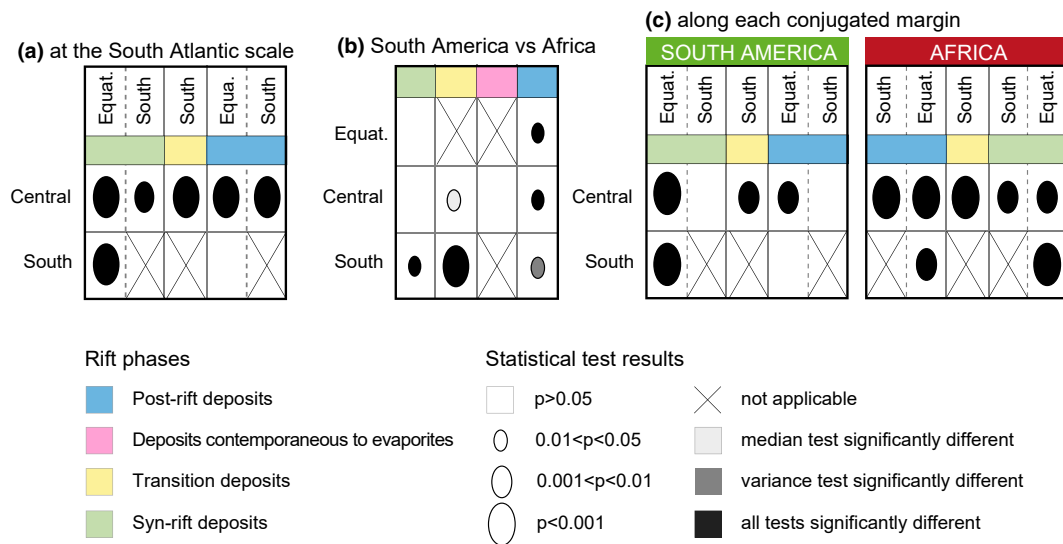


FIGURE 12 Results of the statistical tests assessing, for the different rift phases, the similarities (in terms of average and variability in depositional environments) between the rift phases (a) within each segment, (b) between the conjugated margins of each segment, and (c) between the segments along each margin. If the p -value is higher than .05, the depositional environments of the compared segments are similar (non-significantly different) in terms of their averaged value (extended Mood's test and pairwise median test) and/or their variability (Levene's variance test). Alternatively, the lower the p -value (the larger the oval), the more significantly different are these tested parameters. The lower the p -value ($.01 < p < .05$; $0 < .001 < p < .01$; $p < .001$), the more robust the comparison. Cross ("not applicable") means that a segment cannot be compared with itself. Evaporites are only recorded in the central segment, and transition deposits are not recorded in the equatorial segment. Note that during the transition phase, the averaged depositional environments of the central segment are only weakly different than the other segments (b) while conjugated margins record a similar variability of depositional environments (c). As a difference, during the post-rift phase, the central segment records significantly different environments than the other segments even if their averaged values are similar.

During the transition phase, the basins of the Central and South Segments recorded continental and coastal environments (Figure 9). The depositional environments were statistically significantly deeper in the basins of the South Segment (Figures 10, 11b and 12a) because of the deepening is initiated during the transition phase in the South Segment (Figure 8). They are also statistically

significantly deeper in the African basins than in the South American basins (Figures 10, 11b and 12b).

Deposits contemporaneous of the evaporites recorded continental and coastal deposits (Figure 9). At the scale of the Central Segment, these depositional environments were similar along each margin (Figures 10 and 11b) and between conjugate margins (Figure 12b).

As expected, during the post-rift phase, depositional environments were everywhere significantly deeper than during the previous phases (i.e. the retrograding mega-sequence to shelf to deep marine mean facies; [Figures 9–11c](#)). The ranges of depositional environments were nonetheless highly variable along the margins ([Figures 10, 11c and 12b](#)). After the retrograding mega-sequence, many basins recorded shallowing trends (i.e. prograding mega-sequence; except GHA-2, RIO M-4, LOW CG-6, CG FAN-7, WAL-10, PEL-10; [Figures 6–8](#)).

4.3 | Rifted margin segmentation in the Central Segment

During rifting, the Central Segment margins were segmented into domains of contrasting subsidence and accumulation behaviours. Indeed, in the basins of the Central Segment, the syn-rift depositional environments showed sub-segments with similar continental depositional environments in African and South American basins (ALM-GAB; JEQ-LOW CG) that alternated with segments showing similar continental and coastal environments (e.g. SER-RIO M; [Figures 10 and 11a](#)). In addition, other sub-segments showed slightly deeper depositional environments in either the African basin (CUM-CG FAN) or the South American basin (e.g. PER-DOU).

During the transition phase, this segmentation was smoothed out as depositional environments were similar in African and South American basins ([Figures 10 and 11b](#)). This segmentation even disappeared during evaporite deposition showing homogeneous depositional environments along the margins and between African and South American margins.

During post-rift, this segmentation is visible again with very different depositional environments along and between the African and South American margins ([Figures 10 and 11c](#)). The post-rift phase probably inherited the segmentation of the margin acquired during rifting. Nonetheless, this segmentation was probably controlled as well by the main sediment routing systems draining the continents that induce major changes in accumulations along the margins (e.g. MacGregor, 2013).

5 | DISCUSSION

5.1 | Geodynamical context and timing of the retrograding mega-sequence

The trajectory paths of studied basins show some common trends irrespective of the segment and sub-segment they belong to ([Figures 6–8](#)). The syn-rift phase recorded continental /coastal depositional environments ([Figures 9](#)

and [11a](#)). Where the transition phase was recorded (i.e. Central and South Segment), these shallow depositional environments were sustained during the whole transition phase (i.e. Central Segment; [Figure 7](#)) or part of it (i.e. South Segment; [Figure 8](#)). Afterwards, the post-rift phase recorded mostly shelf to deep marine facies ([Figures 9–11c](#)). This long-term retrograding mega-sequence has been commonly observed in rift and rifted margin basins of the South Atlantic (e.g. Beglinger, Corver, et al., 2012; Beglinger, Doust, et al., 2012a, 2012b; Coward et al., 1999; MacGregor, 2013; Milani et al., 2007; Mohriak, Nemčok, et al., 2008; Séranne & Anka, 2005) and worldwide (e.g. Gawthorpe & Leeder, 2000; Prosser, 1993; Rohais et al., 2007). This deepening trend is indeed expected within the general framework of the stretching of the lithosphere with tectonic subsidence in continental rifts followed by thermal subsidence and deepening of the rifted margin basins (e.g. McKenzie, 1978).

Nevertheless, the phase during which this retrograding mega-sequence occurred varied significantly from one segment of the South Atlantic to the other ([Figure 13](#)). It started: (i) during the syn-rift phase in the basins of the Equatorial Segment ([Figures 6 and 13](#)), (ii) during the transition phase (i.e. after volcanics emplacement) in the basins of the South Segment ([Figures 8 and 13](#)), and (iii) immediately after the end of the transition phase (i.e. drowning of the evaporitic basin), in the basins of Central Segment ([Figures 7 and 13](#)). We discuss below how this timing of the retrograding mega-sequence may be related to the necking style of the margin segments.

5.1.1 | Equatorial Segment—Oblique rift and narrow margins

In the basins of the Equatorial Segment, the retrograding mega-sequence initiated during the syn-rift ([Figure 6](#)). These rifted margins are narrow ($\times 10$ km; e.g. Greenroyd et al., 2008; Jeannot & Buitier, 2018; Loparev et al., 2021; Montenegro et al., 2021; Museur et al., 2020; Sapin et al., 2016; Ye et al., 2019; [Figures 2a and 13b](#)). Narrow margins result from narrow lithosphere necking and are associated with rapid and early tectonic subsidence in the associated basins (e.g. Brune, 2014; Huismans & Beaumont, 2011, 2014; Svartman Dias et al., 2015; Xie & Heller, 2006). This rapid and early subsidence explains the early onset of deepening (i.e. during crustal deformation) as accommodation creation was too rapid to be filled up by sediment supply ([Figure 13d](#)). Narrow margins are also associated with an early break-up with respect to wider margins (e.g. Brune, 2014; Chenin et al., 2020; Huismans & Beaumont, 2011, 2014; Svartman Dias et al., 2015). This could explain the absence of transition phase in the basins of the Equatorial Segment.

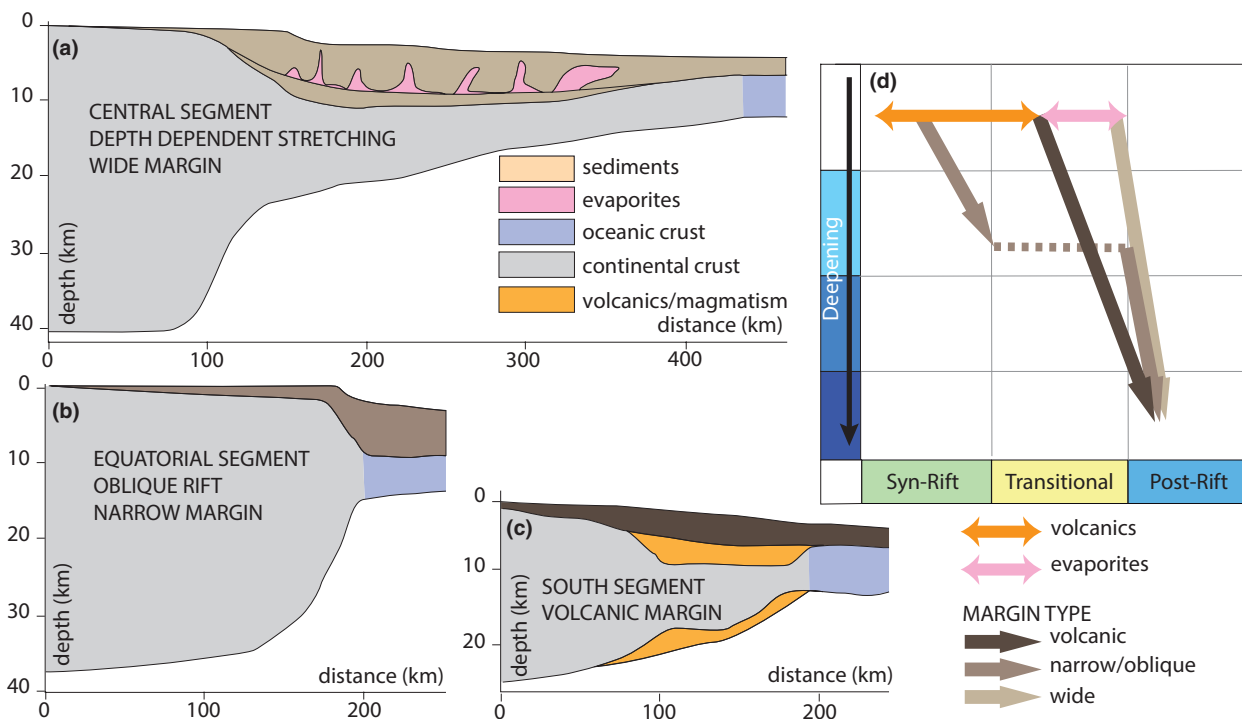


FIGURE 13 Schematized crustal necking styles of (a) wide, (b) volcanic and (c) narrow margins. (d) Timing of the main deepening (and retrograding) mega-sequence for the three types of margins. The timing of the long-term retrograding mega-sequence driven by lithosphere thinning depends on the deformation style and magma production. Along oblique margins of the equatorial segment, deepening is initiated during syn-rift because their narrow crustal thinning style favours rapid tectonic subsidence surpassing sediment supply. Along wide margins of the central segment, deepening is initiated at the end of the transition phase because depth-dependent thinning favours slow tectonic subsidence and late break-up. Along magma-rich margins of the south segment, deepening is initiated during the transition phase, after volcanics stopped filling accommodation created by subsidence.

5.1.2 | Central Segment—Depth-dependent stretching and wide margins

In the basins of the Central Segment, the retrograding mega-sequence occurred at the end of the transition phase (Figure 7). These rifted margins are wide (Figures 2b and 13a) and associated with ductilely deformed lower crust ($\times 100$ km; e.g. Clerc et al., 2018; Epin et al., 2021; Mohriak, Nemčok, et al., 2008; Péron-Pinvidic et al., 2013, 2017; Sapin et al., 2021; Unternehr et al., 2010). Wide margins are associated with slow (and long-lived) tectonic subsidence in the rifted margin basins (e.g. Brune et al., 2017; Chenin et al., 2020; Huisman & Beaumont, 2011, 2014; Svartman Dias et al., 2015; Xie & Heller, 2006). This slow subsidence can explain the shallow depositional environments recorded during the syn-rift and transition phases as accommodation creation was slow enough to be filled-up by sediment supply (Figure 13d). Wide margins are also associated with a delayed crustal break-up with respect to narrower margins corresponding to the migration of crustal deformation from the proximal to the distal margin (e.g. Brune et al., 2017; Huisman & Beaumont, 2011, 2014; Svartman Dias et al., 2015). This delayed break-up

explains the record of the transition phase in the proximal part of the margin (i.e. during the migration of crustal deformation to the distal margin).

5.1.3 | South Segment—Volcanic margins

In the basins of the magmatic margins of the South Segment, the retrograding mega-sequence initiated after volcanics emplacement (Figure 8). Therefore, the shallow depositional environments during volcanism emplacement could be related to the emplacement of volumes of volcanics large enough to fill the accommodation space created by tectonic subsidence (Figure 2c). Accordingly, the deepening of depositional environments after volcanics emplacement could be related to the termination of the volcanic infill of the subsidence-driven accommodation creation (Figure 13d). This is consistent with the fact that, in the Colorado basin without volcanics, the deepening (retrograding mega-sequence) is initiated earlier, during the syn-rift (Figure 8). In the South Segment, the post-rift depositional facies are overall—deeper than along the other two segments (Figure 9). This may be related to the higher density of volcanic deposits with respect to clastic sediments.

5.2 | Geodynamic context of the evaporites

In the Central Segment, evaporites were deposited during the second half of the transition phase, that is, when crustal thinning migrated from the proximal to the distal domains of the margins (Figure 7). Despite the segmentation of the margin during the syn-rift and post-rift phases (see above), the evaporites were deposited within a large basin at the scale of the Central Segment (e.g. Chaboureau et al., 2013 and references therein). In terms of depositional environments, sediments deposited immediately before and during evaporites accumulation were recorded mostly continental and coastal depositional environments (Figures 9–11b). These shallow depositional environments are consistent with the limited crustal thinning in the proximal domain of the margin, especially if the sediment supply was large enough to fill the limited accommodation creation. This does, however, not prescribe the bathymetry of the depositional environments in the distal margin. Evaporite deposition ended at the end of the transition phase with the retrograding mega-sequence, thus, in our framework, immediately following the end of crustal thinning in the distal margin (Figure 7). In all the basins of the Central Segment, the retrograding mega-sequence occurred at the beginning of the post-rift, covering the evaporites with shallow marine carbonates followed by shelf and deep marine sediments (Figures 7 and 13d; Beglinger, Corver, et al., 2012; Beglinger, Doust, et al., 2012a; Coward et al., 1999; Milani et al., 2007; Séranne & Anka, 2005).

5.3 | Geodynamic context of the prograding mega-sequence

In the late post-rift, the retrograding mega-sequence of several basins was followed by a shallowing trend (i.e. the prograding mega-sequence; Figures 6–8). These trends were often associated with prograding clastic wedges (Baby et al., 2018; Brownfield & Charpentier, 2006b; Coward et al., 1999; Dauteuil et al., 2013; Dupré et al., 2007; Milani et al., 2007; Mohriak, Nemčok, et al., 2008; Séranne et al., 1992). They can be related to an increase in clastic sediment supply at the outlet of major continental drainage systems (MacGregor, 2013). Indeed, during the late post-rift, the isotherms deflected by thinning are mostly re-equilibrated and the thermal subsidence is extremely slow (e.g. McKenzie, 1978; Steckler & Watts, 1978). In this context of very slow accommodation creation, any increase in clastic sediment supply, even limited, can

induce significant local shallowing trends and prograding clastic wedges. These increases in sediment supply can be driven either by changes in drainage area and/or in climate (increased precipitation in Western Africa or inland Pelotas after the Oligocene; e.g. Rohais et al., 2021; Séranne & Anka, 2005), or change in rock uplift (e.g. Oligo-Miocene regional uplift of the continental margin in Gabon, Congo and Kwanza basin; Al-Hajri et al., 2009; Lucazeau, 2003; exhumation of the Serra do Mar, Serra da Mantiqueira and craton inland of the Campos, Santos and Pelotas basins; Contreras et al., 2010; Rohais et al., 2021).

6 | CONCLUSIONS

Expanding on the work of Doust (2003), we developed a method to analyse the evolution of depositional environments in sedimentary basins at continental scale. It is based on the normalization of this evolution to tectono-stratigraphic stages (syn-rift, transition and post-rift) rather than to stratigraphic or absolute ages. This normalization allows comparing basins in different geodynamic domains, taking into account only the stage of crustal thinning they reached rather than its timing. To test the approach, we compiled a large database from published data on the basins of the South Atlantic rifted margins and compared the tectono-stratigraphic evolution of the basins in the Equatorial, Central and South segments.

In all the studied basins, we documented the long-term retrograding mega-sequence from continental/coastal syn-rift to shelf/deep marine post-rift depositional environments driven by the stretching of the lithosphere and its subsequent thermal re-equilibration. We show that the relative timing of this retrograding mega-sequence actually depends on the necking style of the rifted margin. In the basins of the narrow oblique margins of the Equatorial Segment, the retrograding mega-sequence initiated during syn-rift because narrow necking style favours rapid tectonic subsidence. In the basins of the wide margins of the Central Segment, the retrograding mega-sequence is initiated at the end of the transition phase because of depth-dependent thinning favours slow tectonic subsidence and late break-up. In the basins of the mama-rich margins of the South Segment, the retrograding mega-sequence initiated during the transition phase, after the emplacement of SDR, when volcanics stopped filling accommodation created by subsidence.

Our compilation shows that, at the scale of the Central Segment, evaporites deposition systematically occurred during the second half of the transition phase, that is to say when crustal thinning migrated to the distal parts of the

margin. We show that, during evaporite deposition, the segmentation of the rifted margins inherited from the syn-rift phase was subdued. Indeed, the depositional environments of sediments immediately before, and contemporaneous of, the evaporites were homogeneously continental and coastal at the scale of the Central segment. Those shallow depositional environments may have been sustained during the transition phase because the proximal domains of the margins underwent only limited thermal subsidence, allowing for the sediment supply to fill the low accommodation creation. Evaporite deposition lasted until the very beginning of the post-rift phase, when the retrograding mega-sequence initiated, that is to say, immediately after the end of crustal thinning in the distal margin.

During the post-rift, we show that the segmentation of the rifted margins of the South Atlantic was recorded again in the evolution of the depositional environments that varied significantly from one basin to the other. In particular, after the retrograding mega-sequence, several basins underwent a prograding mega-sequence that we interpret as a result of local increases in sediment supply at the outlet of major continental drainages in a very low accommodation creation context.

This new type of analysis could be used to analyse the tectono-stratigraphic dynamics of basins at continental scale in many other geodynamic settings and provide reliable relationships between long-term stratigraphic trend with lithosphere and crustal deformation processes.

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CONFLICT OF INTEREST

No, there is no conflict of interest.



PEER REVIEW

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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