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## Paleogeographic evolution of the central segment of the South Atlantic during Early Cretaceous times: Paleotopographic and geodynamic implications

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### Abstract :

The geodynamic processes that control the opening of the central segment of the South Atlantic Ocean (between the Walvis Ridge and the Ascension FZ) are debated. In this paper, we discuss the timing of the sedimentary and tectonic evolution of the Early Cretaceous rift by drawing eight paleogeographic and geodynamic maps from the Berriasian to the Middle-Late Aptian, based on a biostratigraphic (ostracodes and pollen) chart recalibrated on absolute ages (chemostratigraphy, interstratified volcanics, Re-Os dating of the organic matter).

The central segment of the South Atlantic is composed of two domains, with a two phases evolution of the pre-drift ("rifting") times: a rift phase characterized by tilted blocks and growth strata, followed by a sag basin. The southern domain includes the Namibe, Santos and Campos Basins. The northern domain extends from the Espirito Santo and North Kwanza Basins, in the south, to the Sergipe-Alagoas and North Gabon Basins to the north.

Extension started in the northern domain during the Late Berriasian (Congo-Camamu Basin to the Sergipe-Alagoas-North Gabon Basins) and migrated southward. At that time, the southern domain was not a subsiding domain (emplacement of the Parana-Etendeka Trapp). Extension started in this southern domain during the Early Barremian. The rift phase is shorter in the south (5-6 Ma, Barremian to base Aptian) than in the north (19 to 20 Myr, Upper Berriasian to base Aptian). The sag phase is of Middle to Late Aptian age. In the northern domain, this transition corresponds to a hiatus of Early to Middle Aptian age.

From the Late Berriasian to base Aptian, the northern domain evolves from a deep lake with lateral highs to a shallower organic-rich one with no more highs. The lake migrates southward in two steps, until the Valanginian at the border between the northern and southern domains, until the Early Barremian, north of Walvis Ridge.

## Highlights

► Age reevaluation of the basins ► Compilation of eight paleogeographic and deformation maps ► Two main domains with different deformation and sedimentary history ► Diachronous extension from north (Late Berriasian) to south (Early Barremian). ► Transition to brittle rift to sag during Early Aptian, with hiatus in the northern domain.

Keywords : South Atlantic Ocean - central segment, Rift, Early Cretaceous, Paleogeography, Geodynamic

#### 51 **1. Introduction**

The South Atlantic Ocean results from the breakup of Gondwana into two continents, South America and Africa, during Early Cretaceous times. It can be divided into four segments (Moulin et al., 2005): the Falkland segment, south of the Agulhas–Falkland Fracture Zone (AFFZ), the southern segment from the AFFZ to the Rio-Grande FZ, the central segment from the Rio-Grande to the Ascension FZ, and the equatorial segment from the Ascension to the Marathon FZ (Fig. 1).

On both South American and African sides, the central segment is 59 characterized by a sag basin phase (Karner and Driscoll, 1999; Karner 60 et al., 2003: Lentini et al., 2010: Marton et al., 2000), prior to salt 61 deposition and oceanic accretion, and after a rift phase characterized 62 by blocks tilting in the upper continental crust. The sag basin (also 63 called pre-salt sag basin or pre-salt wedge) is characterized by a 64 thick wedge of sediments (3 to 5 km), with no evidence of brittle 65 extension (tilted blocks with syn-sedimentary normal faults with a 66 wavelength of several kilometers to several tens of kilometers). It 67 looks like a large wavelength (several hundreds of kilometers) 68 "flexural" basin. In its proximal part, this sag basin onlaps the tilted 69 blocks mentioned above (Moulin et al., 2005). 70

This two steps evolution, with a rift phase with tilted blocks and 71 growth strata first and a sag phase second, does not fit with classical 72



Fig. 1. Location map of the studied basins at their original position during Berriasian times (plate kinematic model of Moulin et al., 2010), and general map of the different segments of the South Atlantic Ocean (modified from Moulin et al., 2010).

models of uniform lithospheric extension, pure shear (McKenzie,
 1978) and simple shear (Wernicke, 1985) models. Thus, alternative
 depth dependent models were proposed. By applying the model of

Lavier and Manatschal (2006), with brittle layers within the lower 76 crust and the upper mantle, Unternehr et al. (2010) suggest a two 77 phases conservational model (the volume of continental crust at the 78

end of the extension is strictly equal to the initial volume before any 79 80 horizontal movement) with (1) a thinning mode of the lithosphere with brittle deformation and necking of the lower crust in the most 81 distal part and (2) an exhumation mode with denudation of the 82 upper mantle. Aslanian et al. (2009) proposed a non conservational 83 model in three phases, (1) extensive phase (called rift phase) with 84 85 few tilted blocks in the upper continental crust, (2) the exhumation phase (with the sag formation and the salt deposition), main thinning 86 phase mostly involving the lower continental crust and (3) the 87 break-up and oceanic spreading stage. The Huismans and Beaumont's 88 model (2008, 2011), based on lithospheric numerical models with 89 90 depth-dependant extension, implies a weak lower crust, decoupling layer between the crust and the mantle lithosphere, and, as a conse-91quence, a diachronism between the mantle and the upper crust 92thinning. Those models did not agree on several points: the rheology 93 94 of the lithosphere (weak or strong), as well as the nature of the 95 exhumed material, the timing and the synchronicity of the extensional period characterized by blocks tilting and the sag basin. 96

Except for the Aslanian's et al. model (2009), little attention is paid Q597 in those models to paleogeographic and paleotopographic constraints 98 99and consequences. The aim of this study is to establish the *timing of* 100the sedimentary and tectonic evolution of the central segment of the 101 South Atlantic Ocean (Fig. 1), on both sides, during the Early Cretaceous, by drawing *paleogeographic* and geodynamic maps, in order to answer 102103several questions: What is the age of the rift phase with block tilting 104 and the sag periods? Do they overlap through time? If the exhumation models (Aslanian et al., 2009; Lavier and Manatschal, 2006) can be 105applied to this oceanic segment what is the age of this exhumation, 106 time of denudation of the mantle and/or lower continental crusts?, 107 How do the sedimentary environments of the rift and sag periods 108change? What are the surrounding reliefs and catchments? 109

#### 110 2. Geological setting

The beginning of the rifting along the central segment of the South 111 112 Atlantic is of Berriasian age (Campos Neto et al., 2007; Costa et al., 2007; França et al., 2007; Gontijo et al., 2007; Karner and Driscoll, 1131999; Moreira et al., 2007; Rangel et al., 2007; Rodovalho et al., 114 2007; Silva et al., 2007; Winter et al., 2007) and ends with the depo-115116sition of salt during Aptian times. The *initial plate fit* between South 117 America and Africa is still a subject of discussion (Aslanian and Moulin, 2010, 2012; Eagles, 2007; Moulin et al., 2010; Torsvik et al., 118 1192009).

The timing of the rift of the central segment is still being discussed. 120Q6121 Since the pioneer works of Karner et al. (1997, 2003), authors agree 122that there is a two phases evolution, first an extensional period with 123block tilting in the inner upper continental crust, and a second one, corresponding to the so-called sag basin (or pre-salt wedge, pre-salt 124125sag basin, post-rift ante drift). For Karner et al. (2003), this transition 126 is of early Barremian age on the African side. According to the Petrobras Q7127 geologists (Campos Neto et al., 2007; Costa et al., 2007; França et al., 2007; Gontijo et al., 2007; Milani et al., 2007; Moreira et al., 2007; **08**128 Rangel et al., 2007; Rodovalho et al., 2007; Silva et al., 2007; Winter et 129130al., 2007), the base of the sag (called post-rift by them) is recorded by an unconformity (interpreted as the break-up unconformity) which 131132is diachronous along the Brazilian margin, dated pre-Alagoas to neo-133Alagoas, i.e. from base Aptian to Middle-Late Aptian.

Within the first extensional period with blocks tilting, (rift phase of 134Aslanian et al., 2009), several periods of extension were identified 135(Gabon: Teisserenc and Villemin, 1990; Almada-Camamu: Scotchman 136and Chiossi, 2009; Congo: Robert and Yapaudjian, 1990; Cabinda: 137Braccini et al., 1997; Santos: Dyer, 2008). For the South Gabon to 138 139Congo Basins, authors agree that there was a decrease in the extension rate during the rift phase with blocks tilting, i.e. from base Neocomian to 140 Late Barremian-Early Aptian. 141

During the evolution of the rifting (rift phase with tilted 142 blocks + sag), several authors (Guiraud and Maurin, 1991, 1992; 143 Magnavita et al., 2005; Matos, 1992, 1999) suggest variations in the 144 extensional direction, but they do not agree for the timing of these 145 changes. North of the Reconcavo\_South Gabon Basins until the 146 Potiguar\_Benue Basins, Matos (1992, 1999) suggests three changes, 147 EW to ESE\_WNW (Early Berriasian), SE\_NW (Late Berriasian to 148 Early Barremian) and again EW to ESE\_WNW (Late Barremian), while 149 Magnavita et al. (2005) suggest two steps, E\_W (Berriasian\_Valanginian: 150 Rio da Serra stage) and SE\_NW (Barremian\_Aptian, Jiquia stage). At the 151 scale of Africa, Guiraud and Maurin (1991, 1992) show a major change during the Aptian, between a NNE-SSW and an ENE-SSW direction. 153

While the volcanic nature of the austral segment of the South 154 Atlantic, characterized by the presence of seaward-dipping reflectors 155 (SDRs) - subaerial volcanic flows - is well established, the volcanic 156 nature of the margins of the South Atlantic central segment and 157 then the occurrence of seaward-dipping reflectors, are debated 158 (Blaich et al., 2011; Contrucci et al., 2004; Moulin et al., 2005; 159 Reston, 2010). SDRs were expected in the Sergipe and Gabon Basins 160 (Mohriak et al., 1995, 1998), and also southward in the Santos and 161 Campos Basins (Mohriak and Rosendahl, 2003, 2008). According to Q9 Q10 several authors (Blaich et al., 2010, 2011; Contrucci et al., 2004; 163 Moulin et al., 2005), the margins of the central segment are not 164 volcanic margins, because (1) if volcanism occurred locally, it is not 165 a major process for the formation of the margin compare to the 166 austral segment and (2) the subsalt geometries on the seismic lines 167 show structures very different from volcanic margins worldwide. 168

The time of *first occurrence of the oceanic crust* is highly debated, 169 and particularly the relationship with the salt. For the "post-breakup 170 salt" scenario, accretion occurred before salt deposition (Abreu, 1998; 171 Fonck et al., 1998; Guiraud and Maurin, 1992; Jackson et al., 2000; 172 Karner et al., 1997; Marton et al., 2000; Nürnberg and Müller, 173 1991). In this case, the salt basins of the African and Brazilian margins 174 were separated and deposited on a proto-oceanic crust. For the 175 "pre-breakup salt" scenario, seafloor spreading occurred after salt 176 deposition (Davison, 1999; Duval et al., 1992; Evans, 1978; Guardado 177 et al., 1990; Ojeda, 1982), and the substratum of the pre-salt sediment 178 infill would be continental or sub-continental (thinned continental 179 crust, intruded lower continental crust or exhumed mantle material, 180 Moulin et al., 2005).

The geochemical study of the fine-grained sediments of the 182 Congo by Harris (2000) and Harris et al. (2004) provides interesting 183 constraints on the *paleoreliefs, paleoweatherings* and *paleolimnology*. 184 Two phases are identified. The active rift (Sialivakou and Djeno, 185 Neocomian–Early Barremian) corresponds to narrow deep lakes 186 with restricted circulation and low  $0_2$  levels and steep topography 187 on the rift sides with a weathering-limited soil profile and a low to 188 moderate flux of CO<sub>2</sub>. The late rift (Marnes Noires and Argiles vertes, 189 Late Barremian–Aptian) corresponds to broad shallow lakes with low 190  $0_2$  levels in the water column and moderate topography on the rift 191 sides with an intermediate soil profile and a moderate to high flux 192 of CO<sub>2</sub>. This leads to the precipitation of carbonates and a large 193 increase of dissolved SiO<sub>2</sub>.

#### 3. Paleogeographic and geodynamic maps: method

Paleogeographic and geodynamic maps were synthesized from 196 published data. They show, for time slices of a few millions years and 197 with South America and Africa in their position for each period, 198 (1) the distribution of the main facies (paleogeographic maps), from 199 alluvial fans to deep lacustrine environments (with indication of 200 the marine flooding) and (2) the location and the type of basin 201 (geodynamic maps). The three main limits of these maps are (1) the 202 heterogeneity of the data, (2) the age dating and (3) a dataset, limited 203 to the shallowest part of the present-day margin.

Most of the pre-Albian sediments from the central segment of the 206South Atlantic are continental deposits. The fossils available for dating 207are ostracodes and pollen. Regional biozonations (Fig. 2) have been 208209 defined on both sides of the South Atlantic Ocean (Brazil, Reconcavo-210Tucano-Jatoba is a reference: Moura, 1972, Africa: Grosdidier et al., 1996) and an equivalence for the ostracodes biozonations has been 211 proposed by Bate (1999). The key question is the calibration of those 212regional scales on the international stratigraphic chart. 213

On the African side, the regional biostratigraphic scale (Fig. 2) has 214215been established by the Elf biostratigraphers and published by Grosdidier et al. (1996): 11 ostracode biozones labeled from AS2 to 216AS13, 8 pollen biozones labeled from CII to CIX (Doyle et al., 1977, 2171982), and 10 composite biozones (NE1 to NE 3, BA1 to BA 4 and 218 219 AP1 to AP2) (Braccini et al., 1997). For the Brazilian basins, the regional biostratigraphic scale (Fig. 2) has been established by the 220 Petrobras biostratigraphers (Moura, 1972) with 10 ostracode biozones 221(labeled from RT002 to RT009) and 28 ostracode subzones and 10 222 pollen biozones (from P120 to P270) (Arai et al., 1989; Regali et al., 223Q11 224 1974). Schaller (1969) and Viana et al. (1971) proposed local stages for the Lower Cretaceous of the Brazilian margin: Dom Soao, Rio da 225226Serra, Arato, Buracica, Jiquia and Alagoas. Because the synchronicity of the limits of those stages is questionable (Arai et al., 1989, charts pub-227lished by Milani et al., 2007), this nomenclature was not applied here. 228229 Because of the limited connections with the sea, the calibration of these regional biozonations with the standard international strati-230graphic scale, based on marine faunas, is difficult and the arguments 231for the equivalences are not really discussed. Elf biostratigraphers 232(Braccini et al., 1997; Grosdidier et al., 1996) defined three stages 233

Neocomian, Barremian and Aptian, with uncertainties on the exact 234 location of the stage boundaries (Fig. 2). Braccini et al. (1997) proposed 235 absolute ages for the limits of the composite biozones that made 236 it possible to define the Berriasian, Valanginian and Hauterivian 237 stages. On the Brazilian side, the stratigraphic scale (local biozones 238 and international stages) was published by Feijo (1994) and Bueno 239 (2004). They do not agree on the limit of the stages with respect to 240 the same biozonations (Fig. 2).

We used the equivalence of the ostracode biozones proposed by 242 Bate (1999) to compare the ages on both sides of the Atlantic 243 (Fig. 2). They do not fit. The Berriasian–Valanginian boundary on 244 the Brazilian side is equivalent to the Lower–Upper Valanginian 245 boundary on the African side. The Hauterivian–Barremian boundary 246 on the Brazilian side is equivalent to the Lower–Upper Barremian 247 boundary on the African side. 248

This implies that new data must be obtained for an absolute 249 age calibration of these regional biozonations (Fig. 3). We compiled 250 (1) absolute ages available on volcanics interstratified with sediments 251 dated by ostracodes (Santos and Campos Basins) and on organic 252 matter-rich sediments (Re–Os dating technique, Creaser et al., 2008) 253 and (2) chemostratigraphical data (Bueno, 2004) and synthesized 254 them on the chart of the International Commission for Stratigraphy 255 published in 2009 (www:http//stratigraphy.org). Those data are only 256 available on the Brazilian side of the rift. For Re–Os datings, no error 257 bars on the ages are available.

The first level that can be dated correspond to the organic matter-rich 259 shales of the Rio da Serra Brazilian stage (Candeia Formation?) of the 260 Reconcavo Basin, ranging from ostracode biozones 002.2 to 003.2 261 (intra AS3), at around 140 Ma (Creaser et al., 2008, i.e. around the 262 Berriasian–Valanginian boundary). 263



Q2 Fig. 2. Biostratigraphic zonations (ostracodes and pollen) and equivalences on the standard international stratigraphic time-scale (ICS, 2009) for the Cretaceous ante-Albian sediments of the central segment of the South Atlantic Ocean, for both the African and Brazilian sides of the rift. Africa has been taken as a reference for the absolute age calibration, based on the data of Braccini et al. (1997).



Q3 Fig. 3. Absolute age calibration of both African and Brazilian biozonations (ostracodes and pollen) on the standard international stratigraphic time-scale (ICS, 2009), based on chemostratigraphic data (δ<sup>13</sup>C), age of the interstatified volcanism and Re–Os dating of the organic matter.

Based on  $\delta^{13}$ C variations in the Espirito Santo, Cumuruxatiba, Camamu, Reconcavo, Tucano, Sergipe and Alagoas Basins (Bueno, 2004), the Weissert oceanic anoxic event has been identified at the boundary between the Rio da Serra and Aratu Brazilian stages, at the limit of the 004.4 and 004.5 ostracode biozones (intra AS5). This event (Ogg et al., 2008) corresponds to the Lower–Upper Valanginian boundary.

The Cabuinas Formation volcanics of the Campos Basin (interstratified 270with sediments of ostracode biozone 005, intra AS6) have been dated 271from  $122 \pm 5 - 134 \pm 4$  Ma (Mizusaki et al., 1989 in Rangel et al., 1994). 272273The Camboriu Formation volcanics of the Santos Basin (assumed to be of the same age as the Cabuinas Formation) is dated from 130 to 274121 Ma (Moreira et al., 2007). These ages are either K/Ar datings on 275276whole rocks (Campos) or are not specified (Santos). Better ages based on the Ar/Ar technique on plagioclase, are available onshore on the 277dykes, which are possible time-equivalent of the basalts from the 278Camboriu and Cabuinas Formations. These ages range from  $131.4\pm0.5$ 279to  $129.2 \pm 0.4$  Ma (Ponta Grossa dyke swarm, Renne et al., 1996), from 280281 $133.3 \pm 1.7$  to  $129.4 \pm 0.6$  Ma (Rio de Janeiro dyke swarm, Turner et al., 1994) and from  $131.4\pm0.5$  to  $129.2\pm0.4$  Ma (Rio de Janeiro dyke 282 283swarm, Deckart et al., 1998). This suggests that the volcanics, and then ostracode biozone 005, could extend from 131.5 to 129.5 Ma (i.e. around 284the Hauterivian-Barremian boundary). This is supported by the age of 285organic-rich sediments of the Aratu Brazilian stage (?Pojuca Fm), 286ranging from ostracode biozones 005.1 to 005.3, at around 131 Ma 287(Creaser et al., 2008). 288

The organic matter-rich shales of the Lagoa Feia Group (Coqueiros Formation) in the Reconcavo Basin (ostracode biozone 009) are dated at around 125 Ma (Creaser et al., 2008, i.e. around the Barremian–Aptian boundary). The first marine faunas that could be related to the reference 293 standard biozonations are located above the salt and belong to the 294 *Ticinella bajaouaensis* foraminifer biozone (Sergipe basin, Koutsoukos 295 and Bengston, 1993) of Late Aptian age. 296

A stratigraphic chart (Fig. 4) has then been compiled using the 297 biostratigraphic data available on ostracodes and pollen on both 298 sides of the South Atlantic Ocean. 299

#### 3.2. Plate kinematics reconstructions

300

The plate kinematics reconstructions used are those published by 301 Moulin et al. (2010). Intraplate deformations on both Africa and 302 South America plates are now well accepted since the works of 303 Burke and Dewey (1978) and Curie (1984). The model of Moulin 304 et al. (2010), compared to the other models available, takes into 305 account all the offshore and onshore geological and geophysical 306 constraints (e.g. new magnetic anomalies identification) and discuss 307 the occurrence, location and evolution of the intraplate deformations 308 during the opening of the South Atlantic.

The African and South American tectonic plates are subdivided 310 into sub-blocks (4 in Africa, 9 in South America). The limits of the 311 sub-blocks, called intraplate boundaries, correspond to more or 312 less continuous area of deformation, simplified as lines on the 313 map for graphical reasons. In this study, all the paleogeographic 314 maps show the motion of plates and sub-blocks rélative to a fixed 315 specific domain, here the Austral African Block. All finite rotations 316 applied in this work are interpolated from the model of Moulin 317 et al. (2010). 318

Six main environments have been mapped based on the sedimen-320 tological or paleoeocological data available: open marine, hypersaline 321(salt), lacustrine (with turbidites, i.e. deep lake, shallow limestones, 322 and organic matter-rich), deltaic, alluvial plain (distal, proximal) 323 324 and alluvial fans. Alluvial plain deposits correspond to all the alluvial deposits that did not correspond to alluvial fans. Based on the 325 grain size, two types of alluvial plains were defined: coarse-grained 326 sediments should be deposits of bedload fluvial channels and fine-327 grained sediments are those of mixed to suspended-load channels. 328329 Possible highs with no preserved sediments were also reported, as well as hiatuses. 330

The detailed maps are based on the present-day contours of 331 the preserved sediments. Numerous data have been published for 332 )12 333 the African basins (e.g. Anderson et al., 2000; Bate et al., 2001; 334 Braccini et al., 1997; Mbina Mounguengui and Guiraud, 2009; Mbina Mounguengui et al., 2008; Robert and Yapaudjian, 1990; Teisserenc 335and Villemin, 1990). For the Brazilian basins, we used both published 336 sedimentological studies (e.g. Dias et al., 1988; Figueiredo et al., 1994; 337 338 Rangel and Carminatti, 2000) and, when data are missing, facies data available on the detailed stratigraphic charts of Petrobras (Milani 339 340 et al., 2007) are reported on the basin contours. For each map, the names of the mapped lithostratigraphic units are indicated. 341

342 Stratigraphic charts, with detailed facies evolution, were compiled 343 for each basin (Fig. 5).

3.4. Geodynamic maps: active tectonic structures, types of sedimentary
 basins and volcanism

A deformation chart (Fig. 6) has been established. Four types of 346 tectonic settings were defined: pre-rift stage, rift phase with tilted 347 blocks and growth strata, sag and post-rift passive margin, with a 348 focus on the rift and sag phases. Sag basins are recorded by flexural 349350geometries with a wavelength of hundreds of kilometers, unconformably overlapping the tilted blocks of the underlying rift phase. It cor-351352 responds to the pre-salt wedge or pre-salt sag basin of Karner et al. (2003) and Karner and Driscoll (1999) and to the post-rift ante drift 353 of Petrobras geologists (Milani et al., 2007). These data were put 354back onto the previously established stratigraphic chart (Fig. 4). 355

This chart is based on published papers (Brazilian side: Petrobras charts, African side: Robert and Yapaudjian, 1990; Teisserenc and Villemin, 1990) or on the interpretation of published sections (e.g. Dyer, 2008 for the Santos Basin; Braccini et al., 1997 for the Cabinda Basin).

#### 360 4. Stratigraphic and deformation charts: main limits

361 4.1. Stratigraphic charts (Fig. 4)

362Biostratigraphic data are not available for three basins: the Lower Congo, Namibe and Santos Basins. The lithostratigraphy of the Lower 363 Congo Basin (Anderson et al., 2000) is the same as the one applied in 364Cabinda. We extended the Cabinda lithologies and environments to 365 the Lower Congo. The knowledge of the Namibe Basin is more critical, 366 367 because only one publication (Coterill et al., 2002) is available for this key area. We therefore used Coterill's data on the chart; these data 368 indicate a different evolution of the Namibe Basin compared to the 369 370 conjugate Santos Basin. This means either (1) a specific tectonic setting of this basin compared to the Santos Basin (Moulin et al., 3712012) or (2) an error in the age attribution of the volcanics 372(Neocomian-Barremian boundary) by Coterill et al. (2002) that 373 could be younger than expected. In fact, these volcanics could be of 374the same age as the ones of Late Cretaceous (bounded by sediments 375376 of Turonian and Campanian ages) cropping out onshore on the Mossamedes Basin (Carvalho, 1961). Because the age attribution 377 and the stratigraphic sequence pattern of the Santos Basin (Moreira 378

et al., 2007) are similar to those of the Campos Basin (Winter et al., 379 2007), the age of the different formations of the Santos Basin is 380 deduced from the Campos Basin, where biostratigraphic data are 381 available. 382

Some basins have incomplete or contradictory biostratigraphic 383 datasets. For the Kwanza Basin, some ostracode biozones were not 384 formally identified (AS3–4 for the Falçao Limestones and AS3–5 for 385 the Lukunga shales), and a continuity of sedimentation is assumed 386 with the underlying Lukunga Sandstones (AS2) by Bate et al. 387 (2001), from AS2 to AS5. An alternative interpretation could be a 388 hiatus of AS3-4 and AS3-5. In the same area, Bate et al. (2001) 389 suggest, in a figure, a hiatus that is not discussed in the text. This is 390 why we have considered two different scenarios for the Kwanza 391 Basin. For the Cabinda and Campos Basins, several contradictory 392 studies on the lithostratigraphic interpretation have been carried 393 out (Cabinda Basin: Braccini et al., 1997; Karner et al., 2003; 394 McHargue, 1990; Campos Basin: Rangel and Carminatti, 2000; 395 Q13 Winter et al., 2007). In both cases, we kept those for which biostrati- 396 graphic and geological data (wells correlation and geometries) were 397 published (Cabinda Basin: Braccini et al., 1997; Campos Basin: 398 Rangel and Carminatti, 2000). 399

The early stages of deposition of some late subsiding basins are 400 subjects to discussion. No data are available for the age of the base 401 of the Jequitinhonha Basin, dated by comparison with the Espirito 402 Santo and Almada–Camamu Basins. Another key question is the age 403 of the North Gabon Basin (Teisserenc and Villemin, 1990) and then 404 the possible occurrence of sediments older than the N'Toum–Bikele 405 Fm (biozone AS9–11, Teisserenc and Villemin, 1990) that could be 406 equivalent to the lower part of its twin basin, the Jacuipe Basin.

We characterized a hiatus of variable duration through space during the Early–Middle Aptian, except in the Santos Basin. This hiatus is 409 well known on the African side (work by Elf biostratigraphers) and 410 has been defined here on the Brazilian side based on biostratigraphic 411 data published by Petrobras in 1994 (Netto et al., 1994; Santos et al., 412 1994; Vieira et al., 1994). Our interpretation is slightly different than 413 that published by Petrobras in 2007 (Milani et al., 2007), for which 414 biostratigraphic data are not available. Nevertheless, our interpretation is highly dependant of (1) better intercorrelation between the 416 African and Brazilian pollen biozone for Aptian times (dash line 417 Fig. 2 and 4) and (2) a better calibration on the International Stratigraphic Chart.

#### 4.2. Deformation charts (Fig. 6) 420

Few data are available for the Kwanza and Namibe Basins. The chart 421 is based on the sections and chart published in (1) Marton et al. (2000) 422 that identified three steps in the Kwanza Basin (a pre-rift – the Lucula 423 Fm of the same age as the Lukunga Fm, see Fig. 4 – a rift and a sag 424 phase – Cuvo Fm) and (2) Coterill et al. (2002) for the Namibe Basin. 425

The beginning of the rift is discussed in both the Cabinda and 426 Sergipe–Alagoas Basins. In the Cabinda Basin, based on the section 427 published by Braccini et al. (1997) and the sections published by 428 Marton et al. (2000), the rift clearly started after the deposition of 429 the Lucula Fm. For the Sergipe–Alagoas Basin, published sections, 430 limited to the upstream part of the basin (Borba et al., 2011; 431 Chiossi, 2005), suggest an age younger than that published by 432 Petrobras (Campos Neto et al., 2007). 433 Q14

The tectonic setting of the volcanics of the Santos and Campos Basins 434 (Cabuinas and Camboriu Fm) is unclear, with lava flooding prior to or at 435 the same time as the extension (occurrence of syn-sedimentary normal 436 faults during the volcanics)? 437

Some authors have identified several periods with different 438 extension rate and direction. Those can change within the same 439 basin (e.g. Cabinda Basin, Braccini et al., 1997) or are subject to high 440 age uncertainties (e.g. Almada–Camamu Basin, Scotchman and 441 Chiossi, 2009). 442

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\$ aphic (ostraodes and pollen) and lithostratigraphic chart of the Cretacious and Ablan deposits of the central syment of the South Atlantic Ocean. Names with capital letters correspond to lithostratigraphic formations and names with all small letters to lithostratigraphic members. This chart is based on the equivalence of the African neuralional stratagraphic formations and names with all small letters to lithostratigraphic members. This chart is based on the equivalence of the African neuralional stratagraphic formations and names with all small letters to lithostratigraphic members. This chart is based on the equivalence of the African neuralional stratagraphic formations and names with all small letters to lithostratigraphic members. This chart is based on the equivalence of the African neuralional stratagraphic formations and names with all small letters to lithostratigraphic members. This chart is based on the equivalence of the African neuralional stratagraphic formations and names with all small letters to lithostratigraphic members. This chart is based on the equivalence of the African neuralional stratagraphic formations and names with all small letters to lithostratigraphic members. This chart is based on the equivalence of the African neuralional stratagraphic formations and names with all small letters to lithostratigraphic members. This chart is based on the equivalence of the African neuralional stratagraphic formations. 

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Fig. 5. Synthetic charts summarizing the evolution of some key basins: the Santos, Campos, Espirito Santo, Almada–Camamu and Sergipe Basins (Brazil) and Cabinda, Congo, South and North Gabon Basins (Africa). They are all based on the same chart shown in Fig. 4. The absolute age calibration proposed in Fig. 3 has not been used because of its limited spacing through time. Brazilian charts are the one published by Petrobras (Milani et al., 2007). African charts were synthesized based on various publications.

In some rifts, it is difficult to decipher between real syn-443 444 sedimentary faults, post-depositional faults with no growth strata and clear gravity tectonics due to a regional tilting and/or an increase 445of the sediment supply. Gravity tectonics seems very important in 446two aborted rifts: the Reconcavo-Tucano-Jatoba rift (decollement 447 level: Candeias Fm, Cupertino and Bueno, 2005; Magnavita et al., 448 449 2005) and in the Gabon Interior rift (decollement level: Bokoue and Bikoume Fm, Mbina Mounguengui et al., 2008). It is, in both cases, 450very difficult to characterize the periods of crustal brittle extension. 451

#### 452 **5. Paleogeographic and geodynamic maps**

453 5.1. Berriasian–Valanginian boundary (intra ostracode biozone AS3):
454 141–139 Ma

#### 455 5.1.1. Paleogeography

Two domains can be defined bounded by the North Abrolhos Fracture Zone" (present-day boundary between the Espirito Santo and Cumuruxatiba Basins), diffuse zone of deformation along numerous minor faults over a large area, rather than on major localized faults (Fig. 7).

461 Southward, no deposit occurred except, with doubt, the Namibe 462 Basin and the North Kwanza Basin: these two key areas were not 463 biostratigraphically dated of biozone AS3 (see discussion above).

Northward, the sedimentary setting was a deep lake bordered
with alluvial fans, except for the Cumuruxatiba Basin (southwestern
limit of the depositional domain), where alluvial plain sediments
were deposited. Some areas are devoid of sediments: Jequitinhonha
(between the Cumuruxatiba and Camamu Basins), Jacuipe and its
conjugated domain, the North Gabon Basin.

The published stratigraphic and facies charts of the Camamu-470Almada Basins (Caixeta et al., 2007; Gontijo et al., 2007) indicate a 471double supply, from the west and from the east, of these basins. The 472eastward feeding suggests the occurrence of a continental high that 473could be the southern extension of the Jacuipe-North Gabon non de-474475positional domain. This questions the existence of a single lake or of two lacustrine systems, a first one from the Jatoba Basin to the 476Almada–Camamu Basin and a second one from the Sergipe–Alagoas 477 Basins to the Kwanza Basin. We have no argument for choosing 478479between those two scenarios.

Alluvial fans seems limited to the African side (Braccini et al., 1997; Grosdidier et al., 1996; Teisserenc and Villemin, 1990), except along the Camamu–Almada upstream border (Caixeta et al., 2007; Gontijo et al., 2007). This absence on most of the Brazilian side could suggest basins larger than the present-day preserved rifts.

Turbiditic systems were identified as channels in the Camamu–
Almada (charts of Caixeta et al., 2007; Gontijo et al., 2007), Reconcavo
(Silva et al., 2007), Tucano–Jatoba (chart of Costa et al., 2007) and
Sergipe–Alagoas Basins (chart of Campos Neto et al., 2007). On the
African side (South Gabon and Congo), the deep lake is mainly shaley
with few sands (Kissenda and Sialivakou Fm, Robert and Yapaudjian,
1990; Teisserenc and Villemin, 1990).

#### 493 **5.1.2.** *Deformation*

494 Two parallel rifts are active in the northern domain, one westward from the Camamu-Almada Basin to the Jatoba Basin and a second one 495eastward from the Congo-Cabinda Basin to the Sergipe-Alagoas 496Basins, crossing through the Gabon interior Basin. The eastern branch 497could extend southward to North Kwanza. These two rifts are sepa-498 rated by a high that corresponds to the place of sedimentary hiatus 499500discussed above, here called the Central Elevated Block (CEB). The Cumuruxatiba Basin is not yet a rift, but instead is a pre-rift "sag" 501basin. 502

#### 5.2.1. Paleogeography

Two domains can be defined bounded by the Luanda FZ (Fig. 8). 505 Southward, no deposit occurred except along the Namibe Basin 506 where dating is uncertain. 507

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Northward, the sedimentary setting was a large deep lake with 508 widespread turbiditic systems. The Espirito Santo and North Kwanza 509 Basins are subsiding domains. The Jacuipe and North Gabon areas are 510 still not depositional. Petrobras data (Caixeta et al., 2007; Gontijo 511 et al., 2007) again indicate a double supply of the Camamu–Almada 512 Basins from a possible southward continental extension of the 513 Jacuipe–North Gabon domain (CEB). Again the question of the 514 connectivity of the Camamu–Almada, Reconcavo, Tucano, and Jatoba 515 Basins with the rest of the lake is addressed. The age of the beginning 516 of sedimentation in the Jequitinhonha Basin is uncertain and can be of 517 this time period. If it is right, because of the lacustrine nature of the 518 first sediments in the Jequitinhonha Basin (Cricaré Fm), such a 519 connection makes sense. The North Kwanza Basin is the first setting 520 of lacustrine limestones.

Alluvial fans are recorded all along the rift from the Espirito Santo 522 Basin to the Jatoba Basin, on the Brazilian side, and from the Lower 523 Congo to South Gabon Basins on the African side. There are no alluvial 524 fans in the Cumuruxatiba and Jequitinhonha Basins, the Alagoas Basin 525 (post-deposition erosion?) and the Interior Gabon Basin. No information is available for alluvial fans in the North Kwanza Basin. Alluvial 527 plain deposits are mainly located on the Brazilian side, in the Espirito 528 Santo and Cumuruxatiba Basins, but also in the Jatoba and Tucano 529 Basins (beginning of the infilling by subaerial deposits). 530

On the African side, this is the time of coarse-grained turbiditic 531 deposition (Congo: Djeno Fm, Lower Mbr, debris flows and grain 532 flows, Robert and Yapaudjian, 1990; South Gabon: Lucina Fm, channel 533 and lobe deposits, Teisserenc and Villemin, 1990; Interior Gabon: 534 Fourou Plage Fm, Teisserenc and Villemin, 1990) and finer-grained 535 equivalents (Cabinda: Bucomazi Fm, Lower Mbr, Braccini et al., 1997). 536

#### 5.2.2. Deformation and volcanism

The rift is located northward of the Luanda FZ. This single rifting 538 splits into two branches from the Camamu and South Gabon Basins 539 separated by the CEB. 540

The southern domain records the early stages of the Parana– 541 Etendeka volcanic event, mainly located onshore in Brazil. The Santos 542 and Campos Basins are free of volcanics, except for some dyke swarm 543 around Rio de Janeiro and Vitoria–Trinitade (Guedes et al., 2005; 544 Novais et al., 2004). The Espirito Santo (França et al., 2007) and 545 Central Kwanza Basins (Bate et al., 2001) are time equivalents of 546 basalt lava flows and volcanoclastics. 547

5.3. Around the Hauterivian–Barremian boundary (intra ostracode 548 biozone AS6): 131–129 Ma

#### 5.3.1. Paleogeography

Two domains can be defined bounded by the Benguela FZ (Fig. 9). 551 Deposition occurred north of this FZ, except for the Campos Basin 552 where volcanism is observed. This northern domain is again a large 553 deep lake. The northwestern branch (from Camamu to Tucano 554 Basins) is connected to the great lake. The CEB is still a high (double 555 supply of the Camamu–Almada Basins, no sedimentation in the 556 North Gabon Basin) and seems to be an island. But its size is smaller 557 with the beginning of sedimentation in the Jacuipe Basin (Graddi 558 et al., 2007). 559

Turbiditic systems are still active on the African side (Congo: 560 Djeno Fm, Upper Mbr, Robert and Yapaudjian, 1990; South Gabon: 561 Melania Fm, Teisserenc and Villemin, 1990); however, they are 562 more fine-grained around the Cabinda Basin (Bucomazi Fm, Lower 563 Mbr; Braccini et al., 1997) and they do not exist in the Gabon Interior 564

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SAG PHASE

Fig. 6. Beformation chart, superimposed on the biostratigraphic and lithostratigraphic charts in Fig. 4. Two types of basins are here identified: rifls with tilted blocks and growth strata ("rift phase") and sags. Different stages of the rift phase were sometimes defined and are here identified: ac blostratus...

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Fig. 7. Paleogeographic map at the Berriasian–Valanginian boundary (intra ostracode biozone AS3) – 141–139 Ma.



Fig. 8. Paleogeographic map intra Valanginian (intra ostracode biozone AS5) - 137-136 Ma.

Basin. The Brazilian side turbiditic systems occurred from the
Camamu–Almada Basins (charts of Caixeta et al., 2007; Gontijo
et al., 2007) to the Reconcavo Basin (Bruhn, 1999; Magnavita et al.,
2005).

569 Alluvial fans occurred on both sides of the rift, except in the Kwanza 570 (but little sedimentological data have been published), Cumuruxatiba (Rodovalho et al., 2007), Jacuipe (Rangel et al., 2007) and Gabon interior 571 (Mbina Mounguengui et al., 2008) Basins. 572

#### 5.3.2. Deformation and volcanism

The rift is located north of the Benguela FZ, splitting into three 574 branches toward the North: the South-Interior Gabon and Camamu-575



Fig. 9. Paleogeographic map around the Hauterivian–Barremian boundary (intra ostracode biozone AS6) – 131–129 Ma.

Almada Basins that split themselves into two subbranches, the Tucano–
 Jatoba and Jacuipe–Sergipe Basins.

This is the time of widespread volcanism from the Parana Basin to northern Namibia, including the Santos (Camboriu volcanics), Campos (Cabuinas volcanics) and Namibe Basins. This time interval corresponds to the paroxysm of the Parana–Etendeka Trapp (see age synthesis in Moulin et al., 2010).

#### 5.4.1. Paleogeography

For the first time, deposition occurred all along the South Atlantic central segment, from Walvis–Rio Grande to the Ascension FZs. The Central Elevated Block (CEB) is still an island (double supply of the Camanu-Almada Basins, no sedimentation in the North Gabon Basin) (Fig. 10).

5.4. Upper Barremian (ostracode biozone AS8): 128–126 Ma



Fig. 10. Paleogeographic map at the Upper Barremian (ostracode biozone AS8) – 128–126 Ma.

This period records a major paleogeographic change that starts during ostracode biozone AS7 with two clear domains, north and south of the axis Campos to South Kwanza Basins. North, the lake is becoming shallower (Grosdidier et al., 1996) with organic-rich facies (Burwood et al., 1992; Gonçalves, 2001; Mello et al., 1988) and no turbidites. Alluvial fans are limited to the Brazilian side, from the Espirito Santo Basin to the Jatoba Basins (except the Cumuruxatiba and the Jequitinhonha Basins). This suggests an asymmetry of the 596 rift, with low relief on the African side. South, a deep lake occurred 597 with turbidites in the Campos Basin (Rangel and Carminatti, 2000; 598 Q15 Rangel et al., 1994). Alluvial fans are located along the Santos 599 (Moreira et al., 2007) and Campos (Rangel et al., 1994; Winter et al., 600 2007) Basins. Organic-rich sediments were possibly deposited in the 601 Namibe Basin (Coterill et al., 2002). 602

603 **5.4.2.** Deformation

Rifting is active all along the South Atlantic central segment, from Walvis Rio Grande to the Ascension FZs, with two different settings: very active in the south and more quieter in the North. In the south, alluvial fans are active and tilting of the blocks is well recorded in the Campos Basin. In the north, the three northern branches are still active, but the relief (rift shoulders and the water depth contrast) is not as well marked.

611 5.5. Lower Aptian (ostracode biozone AS10): 124–123 Ma

#### 612 5.5.1. Paleogeography

The South Atlantic central segment looks like a single lake, with some
 short marine influences, subdivided into three domains: south (northern
 limit: the axis North Campos to South Kwanza Basins), central (from the
 Espirito Santo–North Kwanza Basins to the Jequitinhonha–Congo Basins)
 and north domains (Fig. 11).

The southern domain (mainly the Santos and Campos Basins) is made of a shallow-water alternation of clays and bioclastic limestones (bivalves coquinas, Carvalho et al., 2000<del>a, 2000b;</del> Moreira et al., 2007; Rangel and Carminatti, 2000), with upstream alluvial fans (Santos, Campos Basins). Evaporites (mainly salt, few anhydrites) occurred just before this time interval (ostracode biozone AS9) in the South Kwanza Basin (Bate et al., 2001).

The central domain shows the same shallow mixed lacustrine siliciclastic\_limestone deposits (bivalves coquinas: Sernambi Fm in the Espirito and Jacuipe Basins, Toca and Banio Fm located on the highs of tilted blocks or as condensed levels in progradational geometries in the Gabon, Congo and Cabinda Basins, Braccini et al., 1997; Harris, 2000; Harris et al., 1994; Robert and Yapaudjian, 1990).

The northern domain is characterized by a major reorganization of 631 the depositional areas: the Reconcavo, Tucano-Jatoba and the Gabon 632 Interior Basins are no longer accumulative, but deposition clearly 633 occurred in the North Gabon Basin (Bikele and N'Toum Fm, Mbina 634 635Mounguengui et al., 2008). Nevertheless, the CEB still exists as suggested by the double eastward and westward supply of the 636 637 Camamu-Almada Basins and the paleocurrents pattern toward the NE in Gabon (Dentale Fm, Smith, 1995). This northern domain is 638 either locally deep, as suggested by turbiditic deposition (Mbina 639 Mounguengui and Guiraud, 2009; Mbina Mounguengui et al., 2008; 640 Teisserenc and Villemin, 1990) or shallow (shallow bioclastic lime-641 642 stones in the Sergipe-Alagoas Basin, Campos Neto et al., 2007).

Alluvial fans are limited to the southern domain. Marine flooding
is recorded (see discussion below) in the Sergipe Basin (fish, Gallo,
2009), South Gabon Basin (marine ostracodes, Grosdidier, 1967),
Q17646 Kwanza Basin (marine ostracodes, Bate, 1999 in Davison and Bate,
2004) and in the Campos Basin (benthic and planktonic foraminifera,
Silva-Telles Jr., 1996 in Dias, 2005).

#### 649 5.5.2. Deformation

Rifting is active all along the South Atlantic central segment, the
southern domain is still more active than the central and northern
domains, as suggested by the alluvial fans. The Reconcavo, TucanoJatoba, and Gabon Interior Basins are no longer subsiding domain;
however a new place of deposition, the North Gabon Basin has been
created. This could mean deformation reorganization in the northern
part of the rift.

This period looks like a transition toward a new tectonic setting(Fig. 12).

659 5.6. Lower Aptian? (intra ostracode biozone AS11): 123-121 Ma

#### 660 5.6.1. Paleogeography

A major hiatus characterized this time period, excepted for the
 Santos and North Gabon Basins. The duration of this hiatus is variable
 through space, as is the age of its beginning and its end (see Fig. 4).

The shallow lake of the Santos Basin is characterized by mixed 664 siliciclastic\_carbonate sediments, from alluvial fans to microbial lime- 665 stones (with stromatolites) with some clay layers (Moreira et al., 666 2007). The North Gabon Basin is continental, fluvial to deep lacustrine 667 sedimentation, as suggested by turbidite deposition (Coniquet Fm, 668 Teisserenc and Villemin, 1990). 669

#### 5.6.2. Deformation

Two different domains can be defined: Santos Basin in the south 671 and all other basins toward the north. The southern domain is no 672 longer a rift. It is a large flexural domain, typical of a sag basin, with 673 local volcanism (Moreira et al., 2007). The possible tectonic meaning 674 of the hiatus will be discussed later, but normal faults are active 675 along the only domain in sedimentation (North Gabon Basin, Mbina Mounguengui and Guiraud, 2009). 677

#### 5.7. Middle Aptian? (intra biozone AP3): 119–116 Ma 678

The width of the South Atlantic segment is becoming the largest. 679 Because most of the well data available are limited to the present 680 day upstream part of the margin, our knowledge of the axial 681 (deepest) part of the basins is poor (Fig. 13). 682

#### 5.7.1. Paleogeography

Again the central segment of the South Atlantic is subdivided into 684 two domains: the Santos and Campos Basins are mainly shallow 685 carbonate lakes, whereas the north is only siliciclastic deposits. 686

The limestones of the Campos and Santos Basins are similar to the 687 limestones of the previous period. They pass laterally to proximal 688 alluvial plain deposits (Moreira et al., 2007; Winter et al., 2007). 689 Toward the north, the rift is more asymmetric, with mainly alluvial 690 deposits in Africa and lacustrine to deltaic with few alluvial plain 691 deposits in Brazil (Fig. 5). The CEB is still a high, but is smaller, with 692 a double supply of the Camamu–Almada Basins, where alluvial fans 693 are still active on the Brazilian side (Gontijo et al., 2007). 694

Evaporites (halite) probably occurred at that time (pollens 695 biozones P230 à P260, Souza-Lima, 2008) in the Alagoas Basin. Ma- 696 rine flooding is expected in the Cabinda Basin on the basis of ostra- 697 codes (Braccini et al., 1997). 698

#### 5.7.2. Deformation

All the basins of the South Atlantic central segment are flexural 700 sags (see Fig. 6 for references). Local normal faults can be locally 701 active or shortly reactivated during this period (Bib–FG). North of 702 the Sergipe–Alagoas Basins, subsidence starts in the Pernambuco 703 Basin (Feijo, 1994). 704

#### 5.8. Middle–Upper Aptian boundary (intra biozone AP4): 116–114 Ma 705

For the same reasons as the Middle Aptian time slice, the nature of 706 the sediments of the axial part of the basins is poorly known and 707 questions the occurrence of evaporites and their relationships with 708 a possible oceanic ridge (Fig. 14). 709

#### 5.8.1. Paleogeography

The entire South Atlantic central segment is covered by evaporites, 711 except in the Jacuipe, Alagoas and Pernambuco Basins, where 712 siliciclastic deposition occurred (Fig. 15). 713 Q18

Evaporites located in the southern part of the South Atlantic 714 central segment (Santos and Campos Basins) are mainly composed 715 of anhydrite and halite (Davison, 2007; Rangel and Carminatti, 716 Q19 2000). Sylvite and carnaillite are reported as a rare occurrence in 717 the Campos Basin (Rangel and Carminatti, 2000). 718 Q20

The northern part is mainly characterized by chloride evaporitic 719 minerals (sylvite, carnaillite and bischofite). The Gabon, Congo and 720 Sergipe Basins show potassium and magnesium chlorides, such as 721

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Fig. 11. Paleogeographic map at the Lower Aptian (ostracode biozone AS10) - 124-123 Ma.

the carnaillite and the tachyhydrite, with thicknesses of tachyhydrite
of a few tens of meters to 100 m (Belmonte et al., 1965; de Ruiter,
Q21 724 1979; Meister and Aurich, 1971; Teisserenc and Villemin, 1990;
Wardlaw, 1972; Wardlaw and Nicholls, 1972).

726 Silicilastic sediments of the Jacuipe to Pernambuco Basins 727 recorded shallow lake conditions with upstream alluvial fans (Alagoas to Pernambuco Basins, Campos Neto et al., 2007; Cordoba 728 et al., 2007). 729

#### 5.8.2. Deformation

The entire South Atlantic central segment is a flexural basin, 731 except toward the north where normal faults are still active in the 732



Fig. 12. Paleogeographic map at the Lower Aptian? (intra ostracode biozone AS11) - 123-121 Ma.

Sergipe–Alagoas Basins (Campos Neto et al., 2007). A proto-oceanic
crust is expected at this time based on the geometrical relationship
of the salt with the oceanic crust (see Petrobras charts, Milani et al.,
2007 and Fig. 5).

#### 6. Discussion: tectonic evolution

#### 737

Two main domains with two different tectonic and paleogeo- 738 graphic evolutions were defined along the South Atlantic central 739



Fig. 13. Paleogeographic map at the Middle Aptian? (intra biozone AP3) - 119-116 Ma.

segment, with a changing boundary through time which propagated 740southward from the Abrolhos FZ (Berriasian–Valanginian boundary) 741 to the Benguela FZ (Hauterivian-Barremian boundary), The boundary 742 between these two domains and the status of the Campos, Espirito 743 Santo and South Kwanza Basins are quite unclear. For Moulin et al. 744 (2012), the Santos Basin-Sao Paulo Plateau system is defined as 745

kinematic "buffer" due to the differential extension between the 746 southern segment of the South Atlantic (south of Walvis Ridge) and 747 the northern domain of the central segment of the South Atlantic. 748 We suggest that this transitional area (Campos, Espirito Santo and 749 South Kwanza Basins) could be a sub-block boundary with highly 750 diffuse deformation. 751



**Fig. 14.** Paleogeographic map at the Middle–Upper Aptian boundary (intra biozone AP4) – 116–114 Ma.

In the upstream part of the present-day margin where data
are available, our results confirm an evolution of the so-called "rift"
(continental extension prior to oceanic accretion) in two phases:
(1) a period characterized by tilted blocks and growth strata (called
rift phase) and (2) a sag phase.

The timing of this evolution is different in the two domains 757 (Fig. 16). In the *northern domain*, north of the Benguela FZ, the litho-758 sphere extension started around the AS2–AS3 biozone boundary that 759 could be Late Berriasian (142–141 Ma) in age (Congo–Almada Basins 760 to Sergipe–Alagoas–North Gabon Basins). It propagated southward 761



**Fig. 15.** Summary paleogeographic and geodynamic maps in eight stages from the Berriasian–Valanginian boundary (intra ostracode biozone AS3) to the Middle–Upper Aptian boundary (intra biozone AP4).



Fig. 15 (continued).





during biozones AS3 and part of AS4, i.e. during the end of the 762 Berriasian and lowermost Valanginian (141-139 Ma). In the southern 763 domain, south of the Benguela FZ, the lithosphere extension started at 764 least after ostracode biozone 005 (=AS7), i.e. during the Early 765 Barremian (130–128 Ma), but an extension contemporaneous of the 766 basaltic floods of the Cabuinas and Camboriu Formations cannot be 767 excluded (see discussion above). This means that the lithosphere ex-768 tension of the central segment of the South Atlantic Ocean migrated 769 southward from the Gabon and NE Brazil to southern Angola and 770 southern Brazil (Santos Basin). 771

The second characteristic feature is the hiatus of sedimentation 772 during the Lower Aptian in the northern domain. As discussed 773 above several models have been proposed for the evolution of the 774 South Atlantic rift: the most recent ones (Aslanian et al., 2009; 775 Huismans and Beaumont, 2008, 2011; Unternehr et al., 2010) suggest 776 an exhumation of the lower crust/upper mantle prior to the sag 777 778 phase. This could correspond to this major hiatus of possible Lower Aptian age. The relative diachronism of this hiatus along the northern 779 domain (see above) reflects a process of variable duration through 780

space, which is a function of the nature of the lithosphere (thickness, 781 rheology, etc.). 782

The sag phase corresponds to a thick wedge (Marton et al., 2000; 783 Lentini et al., 2010) of sediments, unconformably overlapping the 784 underlying sediments. Lentini's isopachs map shows a strong asymmetry between our northern and southern domain, with a mainly 786 African sag in the north and a South American sag in the south and 787 a transition between these two domains where sags occurred on 788 both sides (Espirito Santo and Kwanza Basins). In spite of the poor 789 biostratigraphic resolution of the ostracode biozones and the uncertainties in the equivalence of pollen and ostracode biozones, the sag basin in the north could be older on the African side than on the 792 Brazilian side. 793

A characteristic feature of the northern domain is the occurrence 794 of the Central Elevated Block (CEB), north and south of the N'Komi 795 FZ. The size of this block decreases through time: at its maximum 796 size (base Valanginian), it extends from the Jequitinhonha Basin 797 southward to the Jacuipe–North Gabon Basin. The meaning of this 798 block is not quite clear: it records a splitting into two or three 799



Fig. 16. Summary geodynamic chart of the evolution of the central segment of the South Atlantic Ocean based on the age model proposed in Fig. 3.

branches of the rift, i.e. a change from a narrow (localized deformation) to a wide rift (distributed deformation). This could be due to a
change of the structure of the lithosphere (Brun, 1999; Brun and
Beslier, 1996).

#### 804 7. Discussion: sedimentary and topographic evolution

#### 805 7.1. Lake evolution

Two main types of lakes were identified: deep and shallow. Deep 806 807 lakes could be clayey or sandy, fed by different types of gravity deposits (Reconcavo Basin: Bruhn, 1999; Figueiredo et al., 1994; 808 Gabon to Congo Basins: Bracken, 1994; Smith, 1995; Teisserenc and 809 Villemin, 1990): paleocanyons (Tacuipe, Reconcavo 810 Basin. Magnavita et al., 2005), slumps, channels and lobes. Facies of the shal-811 812 low water lakes are poorly described, except for the carbonated lakes (see descriptions above, bioclastic and/or microbial limestones, 813 Carvalho et al., 2000a, 2000b; Harris, 2000; Harris et al., 1994). The Q22 814 organic matter content of these lakes changes through time (Kuo, 815 1994 – Gabon; Gonçalves, 2001 – Camamu and Almada Basins): 816 the deeper oldest lake (Kissenda or Morro do Barro Fm) is oligotro-817 phic (bacteria, cyanobacteria) and the shallower youngest lake 818 819 (Melania or Rio de Contas Fm) has a higher trophic level and a more complex food chain with abundant eukaryotic organisms. 820 821 Between the two types of lakes, the thermocline (deeper in the 822 shallowest), fetch (higher in the shallowest), water flux (higher in the shallowest), efficiency of nutrient recycling (higher in the 823 shallowest) change. 824

The two domains have a different lake evolution. The northern one starts with deep lake deposits (Late Berriasian, AS3) becoming more and more sandy (increase of the turbiditic supply, Valanginian, AS5). This lake became progressively shallower and was filled by deltas with high clinoforms (Upper Barremian–base Aptian, several hundreds of meters, Crabe–Dentale Fm, Gabon and Congo Basins, Robert and Yapaudjian, 1990). The geomorphic setting of the Early- 831 Middle Aptian hiatus, subaquatic or subaerial, is still unknown. 832 Nevertheless, the progradational nature and then the shallowing 833 upward trend of the Early Aptian sediments (e.g. Dentale Fm, 834 Gabon) can suggest an emersion of the upstream part of the rifts. 835 Few descriptions are available for the facies of the sag basins (Cuvo, 836 Chela and Gamba Fm on the African side, Mariricu Fm from the 837 Espirito Santo Basin to the Jequitinhonha Basin, Upper Taipus Mirim 838 Fm from the Camamu Basin to the Jacuipe Basin, Muribeca Fm in the 839 Sergipe-Alagoas Basins). The southern domain is younger (Upper 840 Barremian, AS8). It is a shallow lake, first siliciclastic and more rich in 841 limestones from the Lower Aptian (AS10) on his Brazilian side. The 842 nature of the sedimentary environments of the Namibe Basin is still 843 poorly constrain during this time interval (hiatus during the upper 844 part of the Early Aptian, marine from the Middle Aptian), in conse- 845 quence, the paleogeography of this domain is quite unclear during 846 Aptian times. 847

#### 7.2. Relief evolution

Two relief wavelengths can be classically associated with the rifts 849 (Cox, 1989; Gilchrist and Summertield, 1994; Ollier, 1985): (1) a 850 dome with a wavelength of hundreds to 1000 km and (2) rift shoulders 851 with a wavelength of several tens of kilometers. 852

No centrifugal fluvial deposits are preserved on either side of the 853 rift. In the Congo Basin ("Congo cuvette"), no sediments of Berriasian 854 to Aptian age are preserved, except eolian Dekese Fm deposits, which 855 are time-equivalent to the Sagri Fm in the Camanu–Almada and 856 Reconcavo Basins (Linol et al., submitted). 857 Q23

We cannot argue either for or against the presence of a *dome* at 858 the time of the beginning of the northern domain rift (Late 859 Berriasian) or at the time of the Parana Etendeka Trapp paroxysm in 860 the southern domain (Late Hauterivian–base Barremian). The only 861 constraint is that the rift is at sea level at the Barremian–Aptian 862

boundary (evaporites in the Kwanza Basin) and during the EarlyAptian (see below).

Two markers record the occurrence of *rift shoulders*: (1) alluvial 865 fans associated with active normal faults and (2) the nature of the 866 sediments and solutes coming from inland and preserved in the rift. 867 In the northern domain, alluvial fans are active on both sides from 868 869 the Upper Berriasian (AS3, Fig. 7) to the base Barremian (AS7). The maximum growth of the alluvial fans and the maximum rate of 870 sediment supply occur during the Valanginian (AS5) with the 871 feeding of all the sandy turbiditic systems. After the Early Barremian, 872 alluvial fans are mainly limited on the Brazilian side (Espirito Santo, 873 874 Camamu-Almada, Reconcavo-Tucano-Jatoba, Jacuipe, and Sergipe-Alagoas Basins). This suggests a maximum relief on the rift flank 875 during the Valanginian, and then a decrease with a high asymmetry 876 during Upper Barremian times. This evolution is in agreement with 877 (1) the few data available on the displacement along the normal 878 879 fault that seems to be at its maximum in the middle part of the rift phase (Fig. 6) and decreases until the end of its activity and (2) the 880 geochemical data (Harris, 2000; Harris et al., 2004) which suggest, 881 on the African side, a decrease of the upstream relief at the time of 882 883 deposition of the organic-rich shales ("Marnes noires" - here dated as Upper Barremian). 884

In the southern domain, alluvial fans are active, on the Brazilian side, from the middle part of the Barremian (AS7) to the base of the salt, i.e. during the rift and the sag phase. This suggests perennial relief in the hinterland of the Santos and Campos Basins, even during the sag phase. No reliable data are available on the African side.

#### 890 7.3. Marine floodings

Marine floodings were identified, based on marine faunas (ostracodes, fish, foraminifers and ammonites) and geochemical characteristics of the sediments or evaporites.

The oldest evidence is not older than base Aptian. Davison and 894 Bate (2004) cites a Late Barremian ostracode (Orthonotacythere 895 mvili) in the Congo rift from Grosdidier (1967). But in the original 896 897 publication, this ostracode is located in the "Wealdian of the Congo coastal basin, upper part" with no further details of its stratigraphic 898 location and age. The first clear evidences of marine faunas are during 899 the Early Aptian, with the occurrence of (1) marine ostracodes 900 (Orthonotacythere) in the Kwanza Basin (Bate, 1999 in Davison and Q24 901 902 Bate, 2004), (2) benthic and planktonic foraminifers in the Campos 903 Basin (Lagoa Feia Fm, Coqueiros Mbr, biozone AS10, Silva-Telles Jr., 1996 in Dias, 2005). (3) marine dinoflagellates (Subtilisphaera) in 904 905the Almada Basin (Lower Alagoas = base Taipus Mirim Fm/Itacaré Mbr, Lana and Pedrao, 2000) (4) fish (Enchodus sp.) in the Sergipe 906 Basin (Morro do Chaves Fm, biozone AS10, Gallo, 2009) and (5) ammo-907 908 nites (Bengston et al., 2007). These marine influences are supported by the occurrence of salts that are older (Barremian-Aptian boundary) in 909 910the Kwanza Basin (Maculungo Fm, Middle Salt Mbr, biozone AS9, Bate, 1999) and younger in the Alagoas Basins (Coqueiro Seco Fm, 911 biozone P230 and Maceio Fm, biozone P260, Campos Neto et al., 2007; 912Feijo, 1994). Hydrogen and carbon isotope geochemistry of the organic 913 matter of the Maculungo Fm (Upper Mbr, biozone AS10, Pedentchouk 914915et al., 2008 and stratigraphy in Pedentchouk et al., 2004) also suggest marine influences at the time of deposition. Surprisingly, true marine 916 influences are not as obvious for the sag phase of the basin. Except for 917 918 the evaporites of the Maceio Fm in the Alagoas Basin, the other place where marine influences were expected is the Cabinda Basin 919 (Chela Fm, Biozone AP3). Braccini et al. (1997) did not mention 920 any specific fossils, but only "probable marine deposits". In the strati-921 graphic synthesis of the Brazilian basins (Milani et al., 2007), a marine 922 (e.g. Sergipe-Alagoas Basin, Campos Neto et al., 2007) or stressed-923 924 transitional marine (e.g. Santos basin, Moreira et al., 2007 or Almada Basin, Gontijo et al., 2007) is evoked for this time interval, but the 925arguments are not published. Such a marine flooding should be coeval 926

with abundant, diversified marine faunas, never published on the 927 African side or on the onshore outcrops of this period in Brazil. 928

Four main periods of flooding can be expected: at the Barremian 929 Aptian boundary (AS9, toward the South), during the Early Aptian 930 (AS10, more widespread), during the Middle(?) Aptian (limited to 931 the north) and around the Middle-Late Aptian boundary (top AS12) 932 with the widespread deposition of the evaporites. 933

The second point is the nature of this marine flooding which is 934 sharp and brief in a lacustrine environment or long-lasting marine 935 environment. (1) Marine evidence is scarce and the very great major-936 ity of the described faunas (ostracodes, fish) are clearly continental 937 ones. (2) The precise sedimentologic and stratigraphic setting of 938 the marine faunas is not really described. Nevertheless, fish from 939 the Sergipe–Alagoas Basin (Morro do Chaves Fm, biozone AS10, 940 Gallo, 2009) indicate "lacustrine environments with some marine 941 influences". 942

The third point is the question of the origin of the marine trans- 943 gression, from the south — South Atlantic flooding above Walvis 944 Ridge or from the north — the Tethys (Central Atlantic). Using the ma- 945 rine dinoflagellates, and mainly the *Subtilisphaera* ecozone, Arai 946 (2009) shows a Tethyan origin of these microfossils common in 947 Venezuela, Senegal and in northern Brazil and suggests the occurrence 948 of a seaway crossing through the Sao Luis, Parnaiba, Araripe and 949 Almada Basins and then the central segment of the South Atlantic. 950

#### 8. Conclusion

Our objective was to establish the *timing of the sedimentary and* 952 *tectonic evolution* of the Early Cretaceous rift of the central segment of 953 the South Atlantic Ocean by drawing *paleogeographic and geodynamic* 954 *maps.* 955

- Eight paleogeographic and deformation maps were drawn from 956 the Berriasian to the Middle–Late Aptian, based on a biostratigraphic 957 (ostracodes and pollen) chart recalibrated on absolute ages 958 (chemostratigraphy, interstratified volcanics, Re–Os dating of 959 the organic matter). Two charts were drawn: a lithostratigraphic 960 and a deformation chart. 961
- 2. The central segment of the South Atlantic is composed of two- 962 domains that have a different history in term of deformation and 963 paleogeography. The southern domain includes the Namibe, 964 Santos and Campos Basins. The northern domain extends from 965 the Espirito Santo and North Kwanza Basins, in the south, to the 966 Sergipe–Alagoas and North Gabon Basins to the north. 967
- 3. We confirmed a two phase evolution of the pre-drift ("rifting") 968 times, with a rift phase characterized by tilted blocks and growth 969 strata in the inner continental crust followed by a flexural sag basin. 970
- 4. Extension started in the northern domain during the Late Berriasian 971 (Congo–Camamu Basin to the Sergipe–Alagoas–North Gabon Basins) 972 and migrated southward. At that time, the southern domain was not 973 a subsiding domain. This is the time of the emplacement of the 974 Parana–Etendeka Trapp (Late Hauterivian–Early Barremian). 975 Extension started in this southern domain during the Early 976 Barremian. The rift phase is shorter in the south (5–6 Ma, Barremian 977 to base Aptian) than in the north (19 to 20 Myr, Upper Berriasian to 978 base Aptian). 979
- 5. From the Late Berriasian to base Aptian, the northern domain evolves 980 from a deep lake with lateral highs to a shallower organic-rich one 981 with no more highs. The lake migrates southward in two steps, 982 until the Valanginian at the border between the northern and 983 southern domains, until the Early Barremian, north of Walvis Ridge. 984
- 6. The sag phase is of Middle to Late Aptian age. In the southern 985 domain, the transition between the rift and the sag phases is 986 continuous. In the northern domain, this transition corresponds 987 to a hiatus of Early to Middle Aptian age. 988

7. Marine influences have clearly been occurring since the Early Aptian
in the northern domain and the Campos Basin. They seem sharp,
with brief flooding coming from the north, i.e. the Tethys-Central
Atlantic, through a seaway crossing South America from the Sao
Luis, Parnaiba, Araripe and Almada Basins (Arai, 1989). In the

absence of data, the importance of these marine floodings episodes

in the Santos Basin is still being debated.

#### Q26 996 9. Uncited references

997 Dias et al., 1994

998 Pedreao and Lana, 2000

999 Uesugui, 1987

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