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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

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 characterized by a sag basin phase (Karner and Driscoll, 1999; Karner et al., 2003; Lentini et al., 2010; Marton et al., 2000), prior to salt deposition and oceanic accretion, and after a rift phase characterized by blocks tilting in the upper continental crust. The sag basin (also called pre-salt sag basin or pre-salt wedge) is characterized by a thick wedge of sediments (3 to 5 km), with no evidence of brittle extension (tilted blocks with syn-sedimentary normal faults with a wavelength of several kilometers to several tens of kilometers). It looks like a large wavelength (several hundreds of kilometers) “flexural” basin. In its proximal part, this sag basin onlaps the tilted blocks mentioned above (Moulin et al., 2005).

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

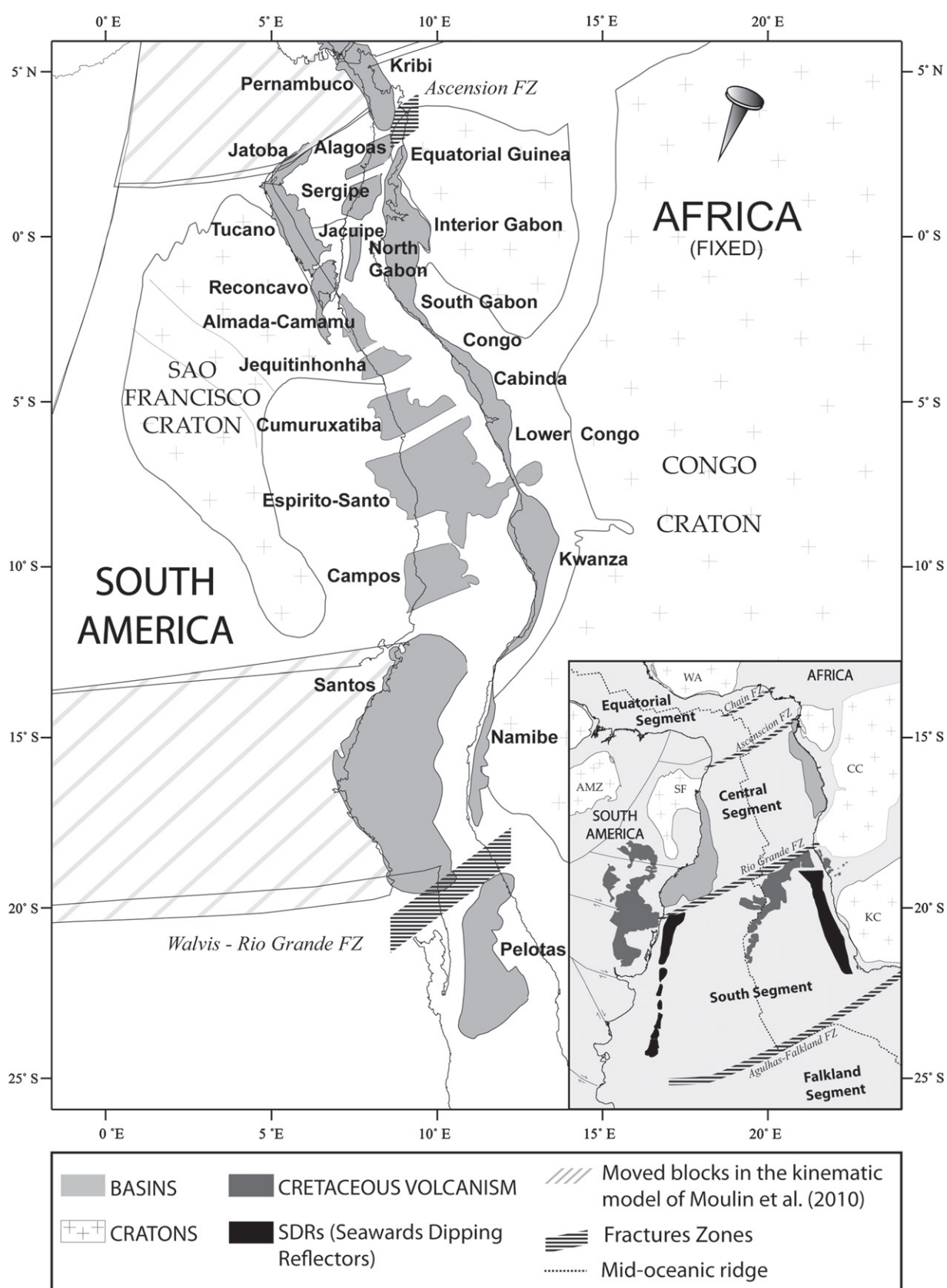


Fig. 1. Location map of the studied basins at their original position during Berriasian times (plate kinematic model of Moulin et al., 2010), and general map of the different segments of the South Atlantic Ocean (modified from Moulin et al., 2010).

73 models of uniform lithospheric extension, pure shear (McKenzie,
74 1978) and simple shear (Wernicke, 1985) models. Thus, alternative
75 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 horizontal movement) with (1) a thinning mode of the lithosphere with brittle deformation and necking of the lower crust in the most distal part and (2) an exhumation mode with denudation of the upper mantle. Aslanian et al. (2009) proposed a non-conservative model in three phases, (1) extensive phase (called rift phase) with few tilted blocks in the upper continental crust, (2) the exhumation phase (with the sag formation and the salt deposition), main thinning phase mostly involving the lower continental crust and (3) the break-up and oceanic spreading stage. The Huismans and Beaumont's model (2008, 2011), based on lithospheric numerical models with depth-dependent extension, implies a weak lower crust, decoupling layer between the crust and the mantle lithosphere, and, as a consequence, a diachronism between the mantle and the upper crust thinning. Those models did not agree on several points: the rheology of the lithosphere (weak or strong), as well as the nature of the exhumed material, the timing and the synchronicity of the extensional period characterized by blocks tilting and the sag basin.

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

2. Geological setting

The beginning of the rifting along the central segment of the South 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, 1999; Moreira et al., 2007; Rangel et al., 2007; Rodovalho et al., 2007; Silva et al., 2007; Winter et al., 2007) and ends with the deposition of salt during Aptian times. The initial plate fit between South America and Africa is still a subject of discussion (Aslanian and Moulin, 2010, 2012; Eagles, 2007; Moulin et al., 2010; Torsvik et al., 2009).

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

Within the first extensional period with blocks tilting, (rift phase of Aslanian et al., 2009), several periods of extension were identified (Gabon: Teisserenc and Villemin, 1990; Almada-Camamu: Scotchman and Chiossi, 2009; Congo: Robert and Yapaudjian, 1990; Cabinda: Braccini et al., 1997; Santos: Dyer, 2008). For the South Gabon to Congo 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 Late Barremian-Early Aptian.

During the evolution of the rifting (rift phase with tilted blocks + sag), several authors (Guiraud and Maurin, 1991, 1992; Magnavita et al., 2005; Matos, 1992, 1999) suggest variations in the extensional direction, but they do not agree for the timing of these changes. North of the Reconco-South Gabon Basins until the Potiguar-Benue Basins, Matos (1992, 1999) suggests three changes, EW to ESE-WNW (Early Berriasian), SE-NW (Late Berriasian to Early Barremian) and again EW to ESE-WNW (Late Barremian), while Magnavita et al. (2005) suggest two steps, E-W (Berriasian-Valanginian: Rio da Serra stage) and SE-NW (Barremian-Aptian, Jiquia stage). At the scale of Africa, Guiraud and Maurin (1991, 1992) show a major change during the Aptian, between a NNE-SSW and an ENE-SSW direction.

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

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

The geochemical study of the fine-grained sediments of the Congo by Harris (2000) and Harris et al. (2004) provides interesting constraints on the paleoreliefs, paleoweatherings and paleolimnology. Two phases are identified. The active rift (Sialivakou and Djeno, Neocomian-Early Barremian) corresponds to narrow deep lakes with restricted circulation and low O₂ levels and steep topography on the rift sides with a weathering-limited soil profile and a low to moderate flux of CO₂. The late rift (Marnes Noires and Argiles vertes, Late Barremian-Aptian) corresponds to broad shallow lakes with low O₂ levels in the water column and moderate topography on the rift sides with an intermediate soil profile and a moderate to high flux of CO₂. This leads to the precipitation of carbonates and a large increase of dissolved SiO₂.

3. Paleogeographic and geodynamic maps: method

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

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

On the African side, the regional biostratigraphic scale (Fig. 2) has been established by the Elf biostratigraphers and published by Grosdidier et al. (1996): 11 ostracode biozones labeled from AS2 to AS13, 8 pollen biozones labeled from CII to CIX (Doyle et al., 1977, 1982), and 10 composite biozones (NE1 to NE 3, BA1 to BA 4 and AP1 to AP2) (Braccini et al., 1997). For the Brazilian basins, the regional biostratigraphic scale (Fig. 2) has been established by the Petrobras biostratigraphers (Moura, 1972) with 10 ostracode biozones (labeled from RT002 to RT009) and 28 ostracode subzones and 10 pollen biozones (from P120 to P270) (Arai et al., 1989; Regali et al., 1974). Schaller (1969) and Viana et al. (1971) proposed local stages for the Lower Cretaceous of the Brazilian margin: Dom Soao, Rio da Serra, Arato, Buracica, Jiquia and Alagoas. Because the synchronicity of the limits of those stages is questionable (Arai et al., 1989, charts published by Milani et al., 2007), this nomenclature was not applied here.

Because of the limited connections with the sea, the calibration of these regional biozonations with the standard international stratigraphic scale, based on marine faunas, is difficult and the arguments for the equivalences are not really discussed. Elf biostratigraphers (Braccini et al., 1997; Grosdidier et al., 1996) defined three stages

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

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

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

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

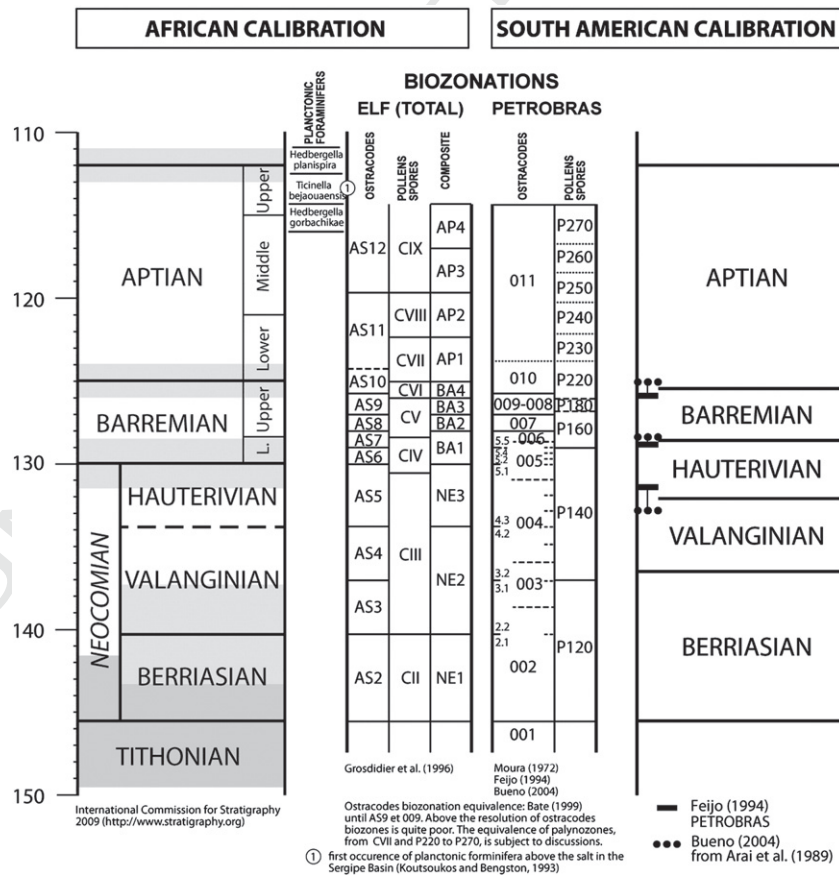
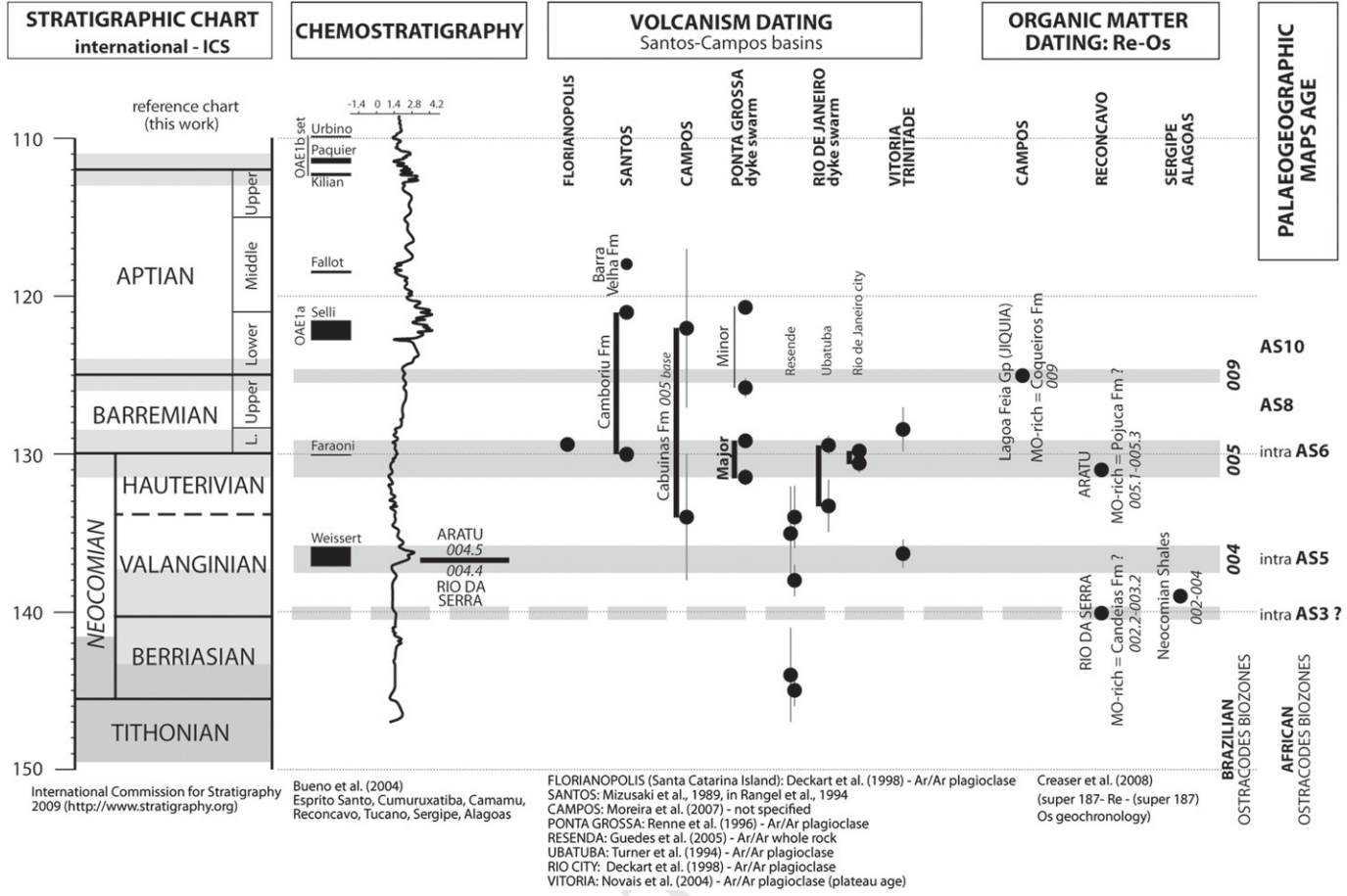


Fig. 2. Biostratigraphic zonations (ostracodes and pollen) and equivalences on the standard international stratigraphic time-scale (ICS, 2009) for the Cretaceous ante-Albian sediments of the central segment of the South Atlantic Ocean, for both the African and Brazilian sides of the rift. Africa has 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 ($\delta^{13}\text{C}$), age of the interstratified volcanism and Re-Os dating of the organic matter.

264 Based on $\delta^{13}\text{C}$ variations in the Espirito Santo, Cumuruxatiba, 293
 265 Camamu, Reconcavo, Tucano, Sergipe and Alagoas Basins (Bueno, 2004), 294
 266 the Weissert oceanic anoxic event has been identified at the boundary 295
 267 between the Rio da Serra and Aratu Brazilian stages, at the limit of the 296
 268 Rio da Serra and Aratu Brazilian stages, at the limit of the 004.4 297
 269 and 004.5 ostracode biozones (intra AS5). This event (Ogg et al., 2008) 298
 270 corresponds to the Lower-Upper Valanginian boundary. 299

271 The Cabuinas Formation volcanics of the Campos Basin (interstratified 300
 272 with sediments of ostracode biozone 005, intra AS6) have been dated 301
 273 from 122 ± 5 – 134 ± 4 Ma (Mizusaki et al., 1989 in Rangel et al., 1994). 302
 274 The Camboriu Formation volcanics of the Santos Basin (assumed to be 303
 275 of the same age as the Cabuinas Formation) is dated from 130 to 304
 276 121 Ma (Moreira et al., 2007). These ages are either K/Ar datings on 305
 277 whole rocks (Campos) or are not specified (Santos). Better ages based 306
 278 on the Ar/Ar technique on plagioclase, are available onshore on the 307
 279 dykes, which are possible time-equivalent of the basalts from the 308
 280 Camboriu and Cabuinas Formations. These ages range from 131.4 ± 0.5 309
 281 to 129.2 ± 0.4 Ma (Ponta Grossa dyke swarm, Renne et al., 1996), from 310
 282 133.3 ± 1.7 to 129.4 ± 0.6 Ma (Rio de Janeiro dyke swarm, Turner et al., 311
 283 1994) and from 131.4 ± 0.5 to 129.2 ± 0.4 Ma (Rio de Janeiro dyke 312
 284 swarm, Deckart et al., 1998). This suggests that the volcanics, and then 313
 285 ostracode biozone 005, could extend from 131.5 to 129.5 Ma (i.e. around 314
 286 the Hauterivian–Barremian boundary). This is supported by the age of 315
 287 organic-rich sediments of the Aratu Brazilian stage (?Pojuca Fm), 316
 288 ranging from ostracode biozones 005.1 to 005.3, at around 131 Ma 317
 289 (Creaser et al., 2008). 318

290 The organic matter-rich shales of the Lagoa Feia Group (Coqueiros 319
 291 Formation) in the Reconcavo Basin (ostracode biozone 009) are dated 320
 292 at around 125 Ma (Creaser et al., 2008, i.e. around the Barremian–Aptian 321
 293 boundary). 322

293 The first marine faunas that could be related to the reference 293
 294 standard biozonations are located above the salt and belong to the 294
 295 *Ticinella bajaouaensis* foraminifer biozone (Sergipe basin, Koutsoukos 295
 296 and Bengston, 1993) of Late Aptian age. 296

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

3.2. Plate kinematics reconstructions 300

301 The plate kinematics reconstructions used are those published by 301
 302 Moulin et al. (2010). Intraplate deformations on both Africa and 302
 303 South America plates are now well accepted since the works of 303
 304 Burck and Dewey (1978) and Curie (1984). The model of Moulin 304
 305 et al. (2010), compared to the other models available, takes into 305
 306 account all the offshore and onshore geological and geophysical 306
 307 constraints (e.g. new magnetic anomalies identification) and discuss 307
 308 the occurrence, location and evolution of the intraplate deformations 308
 309 during the opening of the South Atlantic. 309

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

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

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

Stratigraphic charts, with detailed facies evolution, were compiled 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 tectonic settings were defined: pre-rift stage, rift phase with tilted blocks and growth strata, sag and post-rift passive margin, with a focus on the rift and sag phases. Sag basins are recorded by flexural geometries with a wavelength of hundreds of kilometers, unconformably overlapping the tilted blocks of the underlying rift phase. It corresponds 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 of Petrobras geologists (Milani et al., 2007). These data were put back onto the previously established stratigraphic chart (Fig. 4).

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).

4. Stratigraphic and deformation charts: main limits

4.1. *Stratigraphic charts (Fig. 4)*

Biostratigraphic data are not available for three basins: the Lower Congo, Namibe and Santos Basins. The lithostratigraphy of the Lower Congo Basin (Anderson et al., 2000) is the same as the one applied in Cabinda. We extended the Cabinda lithologies and environments to the Lower Congo. The knowledge of the Namibe Basin is more critical, 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 indicate a different evolution of the Namibe Basin compared to the conjugate Santos Basin. This means either (1) a specific tectonic setting of this basin compared to the Santos Basin (Moulin et al., 2012) or (2) an error in the age attribution of the volcanics (Neocomian-Barremian boundary) by Coterill et al. (2002) that could be younger than expected. In fact, these volcanics could be of the same age as the ones of Late Cretaceous (bounded by sediments of Turonian and Campanian ages) cropping out onshore on the Mossamedes Basin (Carvalho, 1961). Because the age attribution and the stratigraphic sequence pattern of the Santos Basin (Moreira

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

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

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

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

4.2. *Deformation charts (Fig. 6)*

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

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

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

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

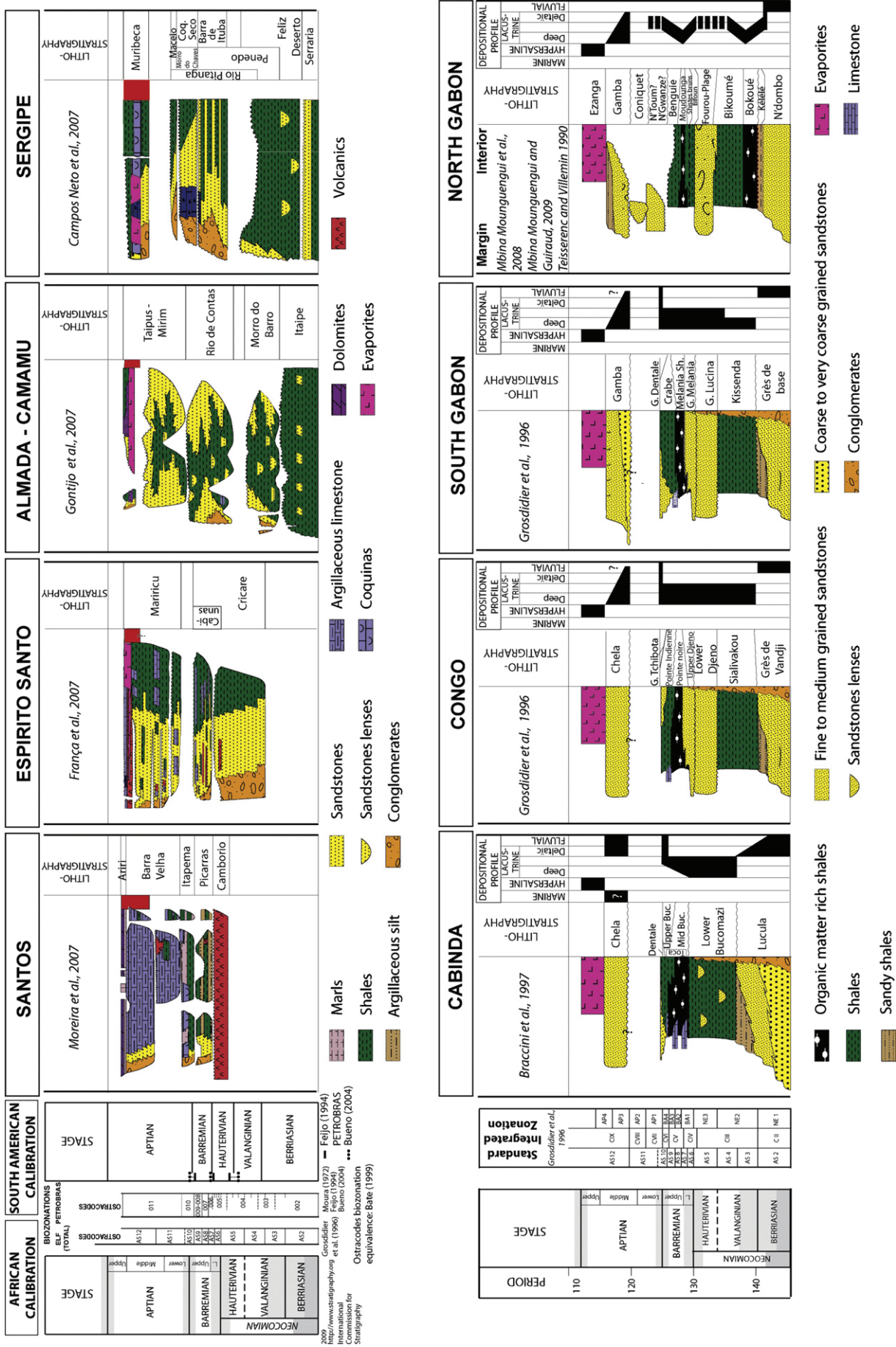


Fig. 5. Synthetic charts summarizing the evolution of some key basins: the Santos, Campos, Espirito Santo, Almada-Camamu and Sergipe Basins (Brazil) and Cabinda, Congo, South and North Gabon Basins (Africa). They are all based on the same chart shown in Fig. 4. The absolute age calibration proposed in 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-sedimentary faults, post-depositional faults with no growth strata and clear gravity tectonics due to a regional tilting and/or an increase of the sediment supply. Gravity tectonics seems very important in two aborted rifts: the Reconcavo–Tucano–Jatoba rift (decollement level: Candeias Fm, [Cupertino and Bueno, 2005](#); [Magnavita et al., 2005](#)) and in the Gabon Interior rift (decollement level: Bokoue and Bikoume Fm, [Mbina Mounquengui et al., 2008](#)). It is, in both cases, very difficult to characterize the periods of crustal brittle extension.

5. Paleogeographic and geodynamic maps

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

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](#)).

Southward, no deposit occurred except, with doubt, the Namibe Basin and the North Kwanza Basin: these two key areas were not 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–Almada Basins ([Caixeta et al., 2007](#); [Gontijo et al., 2007](#)) indicate a double supply, from the west and from the east, of these basins. The eastward feeding suggests the occurrence of a continental high that could be the southern extension of the Jacuipe–North Gabon non depositional domain. This questions the existence of a single lake or of two lacustrine systems, a first one from the Jatoba Basin to the Almada–Camamu Basin and a second one from the Sergipe–Alagoas Basins to the Kwanza Basin. We have no argument for choosing between 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](#)).

5.1.2. Deformation

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

5.2. Intra Valanginian (intra ostracode biozone AS5): 137–136 Ma 503

5.2.1. Paleogeography 504

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

Northward, the sedimentary setting was a large deep lake with widespread turbiditic systems. The Espirito Santo and North Kwanza Basins are subsiding domains. The Jacuipe and North Gabon areas are still not depositional. Petrobras data ([Caixeta et al., 2007](#); [Gontijo et al., 2007](#)) again indicate a double supply of the Camamu–Almada Basins from a possible southward continental extension of the Jacuipe–North Gabon domain (CEB). Again the question of the connectivity of the Camamu–Almada, Reconcavo, Tucano, and Jatoba Basins with the rest of the lake is addressed. The age of the beginning of sedimentation in the Jequitinhonha Basin is uncertain and can be of this time period. If it is right, because of the lacustrine nature of the first sediments in the Jequitinhonha Basin (Cricaré Fm), such a connection makes sense. The North Kwanza Basin is the first setting of lacustrine limestones. 510 511 512 513 514 515 516 517 518 519 520 521

Alluvial fans are recorded all along the rift from the Espirito Santo Basin to the Jatoba Basin, on the Brazilian side, and from the Lower Congo to South Gabon Basins on the African side. There are no alluvial fans in the Cumuruxatiba and Jequitinhonha Basins, the Alagoas Basin (post-deposition erosion?) and the Interior Gabon Basin. No information is available for alluvial fans in the North Kwanza Basin. Alluvial plain deposits are mainly located on the Brazilian side, in the Espirito Santo and Cumuruxatiba Basins, but also in the Jatoba and Tucano Basins (beginning of the infilling by subaerial deposits). 522 523 524 525 526 527 528 529 530

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

5.2.2. Deformation and volcanism 537

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

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

5.3. Around the Hauterivian–Barremian boundary (intra ostracode biozone AS6): 131–129 Ma 548 549

5.3.1. Paleogeography 550

Two domains can be defined bounded by the Benguela FZ ([Fig. 9](#)). 551

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

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

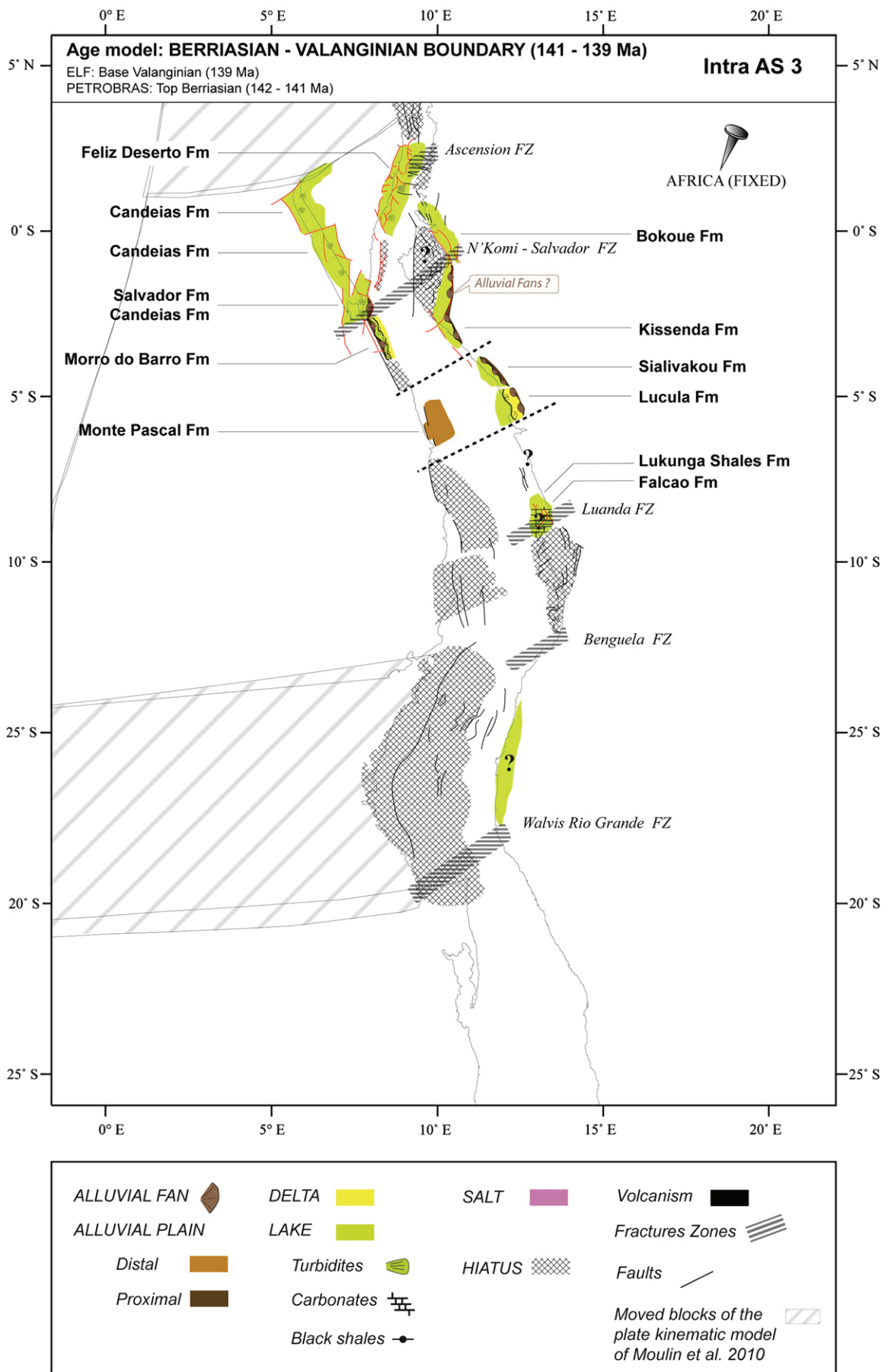


Fig. 7. Paleogeographic map at the Berriasian–Valanginian boundary (intra ostracode biozone AS3) – 141–139 Ma.

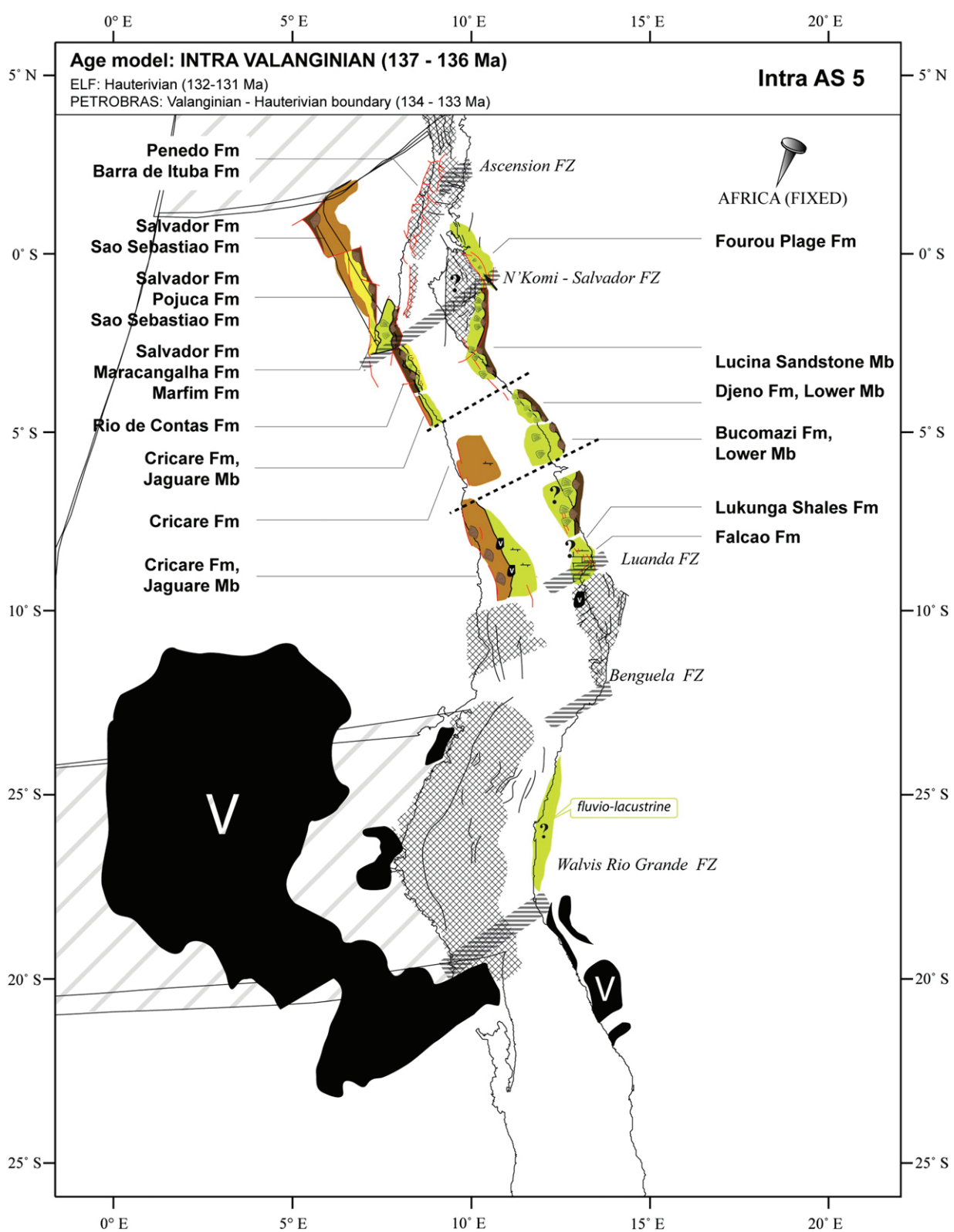


Fig. 8. Paleogeographic map intra Valanginian (intra ostracode biozone AS5) – 137–136 Ma.

565 Basin. The Brazilian side turbiditic systems occurred from the
 566 Camamu–Almada Basins (charts of Caixeta et al., 2007; Gontijo
 567 et al., 2007) to the Reconcavo Basin (Bruhn, 1999; Magnavita et al.,
 568 2005).

569 Alluvial fans occurred on both sides of the rift, except in the Kwanza
 570 (but little sedimentological data have been published), Cumuruxatiba

(Rodvalho et al., 2007), Jacuibe (Rangel et al., 2007) and Gabon interior 571
 (Mbina Mounquengui et al., 2008) Basins. 572

5.3.2. Deformation and volcanism 573

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

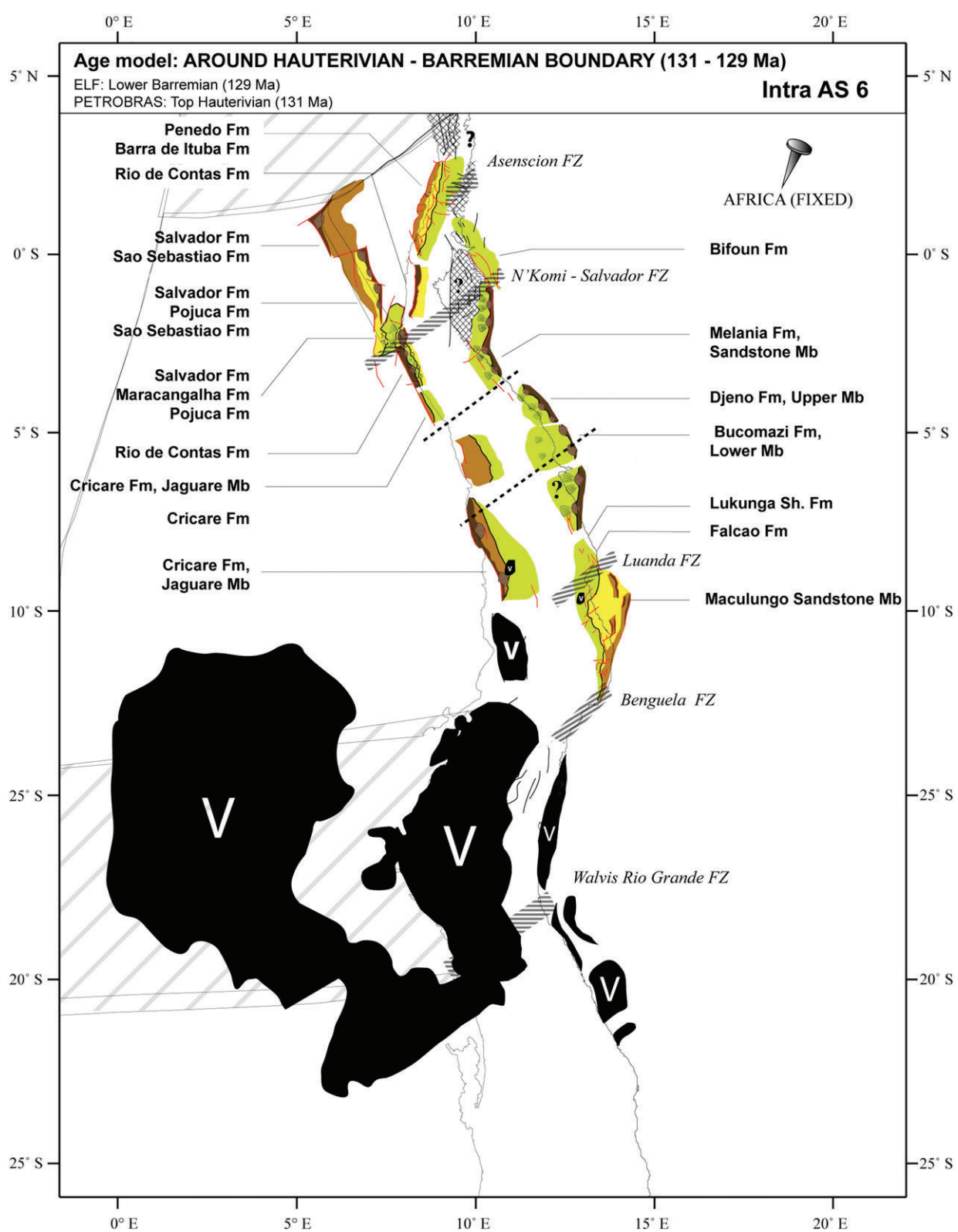


Fig. 9. Paleogeographic map around the Hauterivian–Barremian boundary (intra ostracode biozone AS6) – 131–129 Ma.

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

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

583 5.4. Upper Barremian (ostracode biozone AS8): 128–126 Ma

5.4.1. Paleogeography

584 For the first time, deposition occurred all along the South Atlantic
585 central segment, from Walvis–Rio Grande to the Ascension FZs. The Central
586 Elevated Block (CEB) is still an island (double supply of the Camamu–
587 Almada Basins, no sedimentation in the North Gabon Basin) (Fig. 10).
588

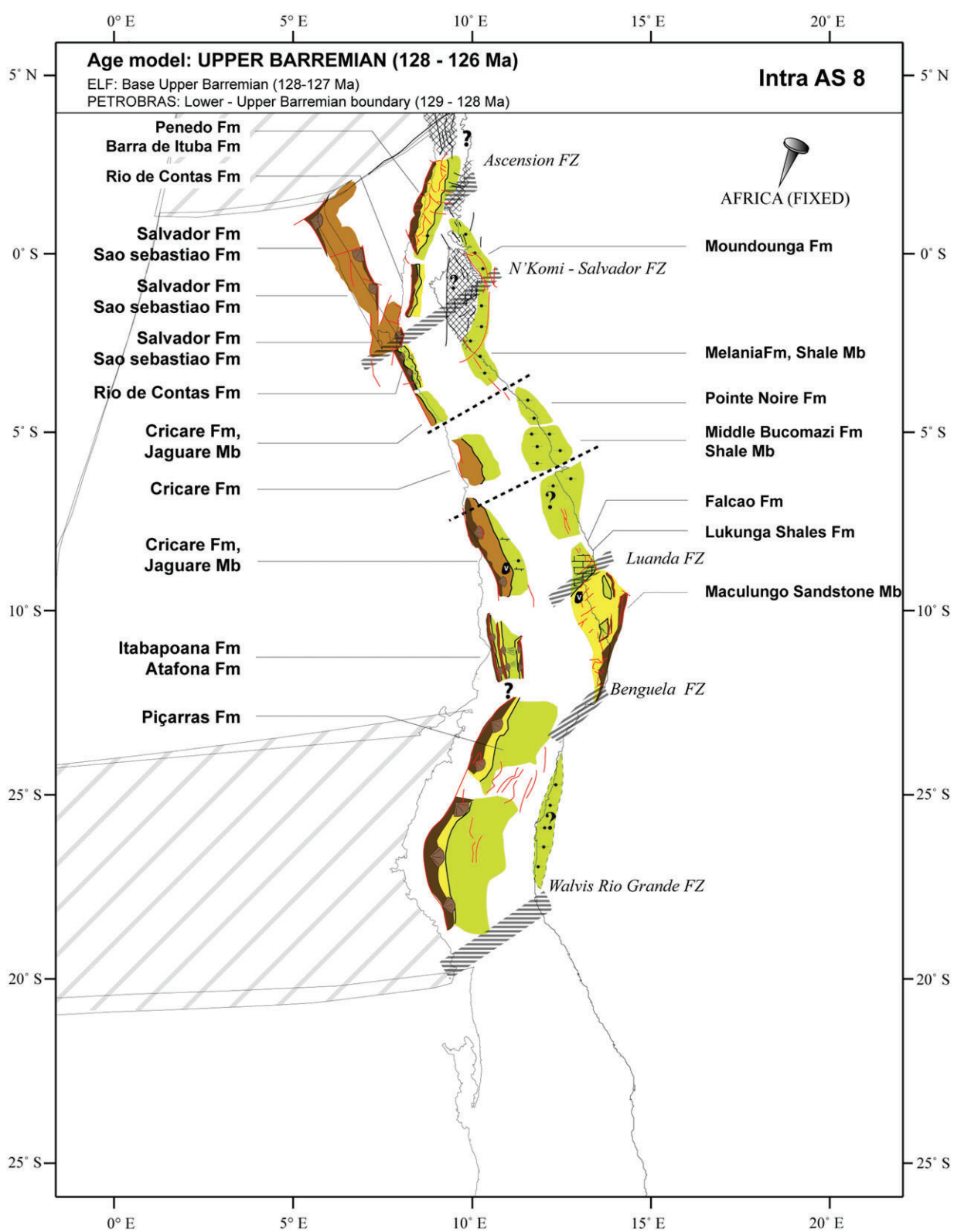


Fig. 10. Paleogeographic map at the Upper Barremian (ostracode biozone AS8) — 128–126 Ma.

589 This period records a major paleogeographic change that starts
 590 during ostracode biozone AS7 with two clear domains, north and
 591 south of the axis Campos to South Kwanza Basins. North, the lake is
 592 becoming shallower (Grosdidier et al., 1996) with organic-rich facies
 593 (Burwood et al., 1992; Gonçalves, 2001; Mello et al., 1988) and no
 594 turbidites. Alluvial fans are limited to the Brazilian side, from the
 595 Espírito 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 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	664
604	Rifting is active all along the South Atlantic central segment, from	665
605	Walvis Rio Grande to the Ascension FZs, with two different settings:	666
606	very active in the south and more quieter in the North. In the south,	667
607	alluvial fans are active and tilting of the blocks is well recorded in	668
608	the Campos Basin. In the north, the three northern branches are still	669
609	active, but the relief (rift shoulders and the water depth contrast) is	
610	not as well marked.	
611	5.5. Lower Aptian (ostracode biozone AS10): 124–123 Ma	
612	5.5.1. Paleogeography	
613	The South Atlantic central segment looks like a single lake, with some	
614	short marine influences, subdivided into three domains: south (northern	
615	limit: the axis North Campos to South Kwanza Basins), central (from the	
616	Espirito Santo–North Kwanza Basins to the Jequitinhonha–Congo Basins)	
617	and north domains (Fig. 11).	
618	The southern domain (mainly the Santos and Campos Basins) is	
619	made of a shallow-water alternation of clays and bioclastic lime-	
Q16 620	stones (bivalves coquinas, Carvalho et al., 2000a,–2000b; Moreira	
621	et al., 2007; Rangel and Carminatti, 2000), with upstream alluvial	
622	fans (Santos, Campos Basins). Evaporites (mainly salt, few anhydrites)	
623	occurred just before this time interval (ostracode biozone AS9) in the	
624	South Kwanza Basin (Bate et al., 2001).	
625	The central domain shows the same shallow mixed lacustrine	
626	siliciclastic–limestone deposits (bivalves coquinas: Sernambi Fm in	
627	the Espirito Santo and Jacuipe Basins, Toca and Banio Fm located on the	
628	highs of tilted blocks or as condensed levels in progradational geom-	
629	etries in the Gabon, Congo and Cabinda Basins, Braccini et al., 1997;	
630	Harris, 2000; Harris et al., 1994; Robert and Yapaudjian, 1990).	
631	The northern domain is characterized by a major reorganization of	
632	the depositional areas: the Reconcavo, Tucano–Jatoba and the Gabon	
633	Interior Basins are no longer accumulative, but deposition clearly	
634	occurred in the North Gabon Basin (Bikele and N'Toum Fm, Mbina	
635	Mounguengui et al., 2008). Nevertheless, the CEB still exists as	
636	suggested by the double eastward and westward supply of the	
637	Camamu–Almada Basins and the paleocurrents pattern toward the	
638	NE in Gabon (Dentale Fm, Smith, 1995). This northern domain is	
639	either locally deep, as suggested by turbiditic deposition (Mbina	
640	Mounguengui and Guiraud, 2009; Mbina Mounguengui et al., 2008;	
641	Teisserenc and Villemin, 1990) or shallow (shallow bioclastic lime-	
642	stones in the Sergipe–Alagoas Basin, Campos Neto et al., 2007).	
643	Alluvial fans are limited to the southern domain. Marine flooding	
644	is recorded (see discussion below) in the Sergipe Basin (fish, Gallo,	
645	2009), South Gabon Basin (marine ostracodes, Grosdidier, 1967),	
Q17 646	Kwanza Basin (marine ostracodes, Bate, 1999 in Davison and Bate,	
647	2004) and in the Campos Basin (benthic and planktonic foraminifera,	
648	Silva-Telles Jr., 1996 in Dias, 2005).	
649	5.5.2. Deformation	
650	Rifting is active all along the South Atlantic central segment, the	
651	southern domain is still more active than the central and northern	
652	domains, as suggested by the alluvial fans. The Reconcavo, Tucano–	
653	Jatoba, and Gabon Interior Basins are no longer subsiding domain;	
654	however a new place of deposition, the North Gabon Basin has been	
655	created. This could mean deformation reorganization in the northern	
656	part of the rift.	
657	This period looks like a transition toward a new tectonic setting	
658	(Fig. 12).	
659	5.6. Lower Aptian? (intra ostracode biozone AS11): 123–121 Ma	
660	5.6.1. Paleogeography	
661	A major hiatus characterized this time period, excepted for the	
662	Santos and North Gabon Basins. The duration of this hiatus is variable	
663	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	670
	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	676
	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	683
	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	699
	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	710
	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 carnallite 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, carnallite and bischofite). The Gabon, Congo and	720
	Sergipe Basins show potassium and magnesium chlorides, such as	721

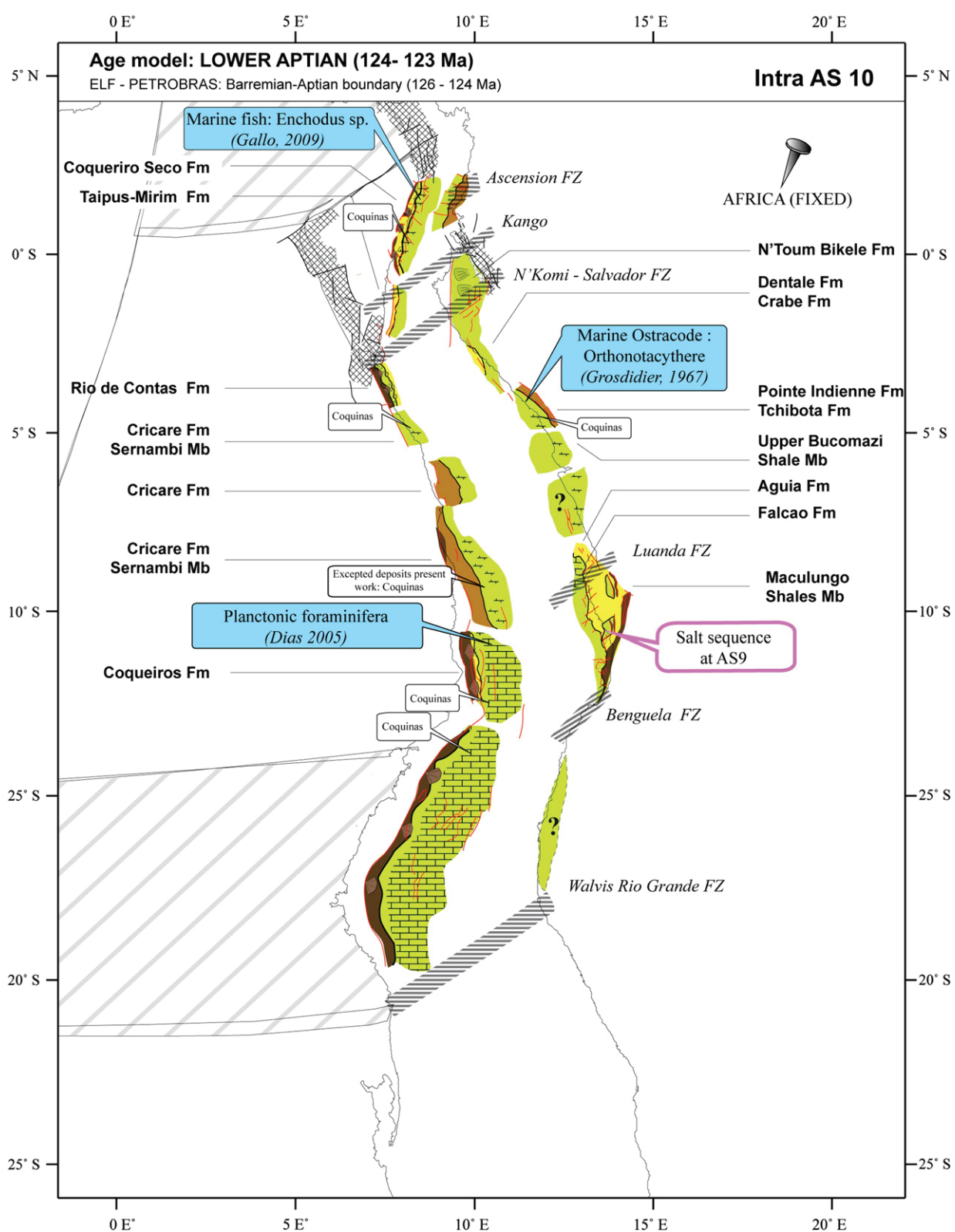


Fig. 11. Paleogeographic map at the Lower Aptian (ostracode biozone AS10) – 124-123 Ma.

722 the carnallite and the tachyhydrite, with thicknesses of tachyhydrite
 723 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;
 725 Wardlaw, 1972; Wardlaw and Nicholls, 1972).

726 Siliclastic sediments of the Jacuibe to Pernambuco Basins
 727 recorded shallow lake conditions with upstream alluvial fans

(Alagoas to Pernambuco Basins, Campos Neto et al., 2007; Cordoba
 et al., 2007). 728 729

5.8.2. Deformation 730

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

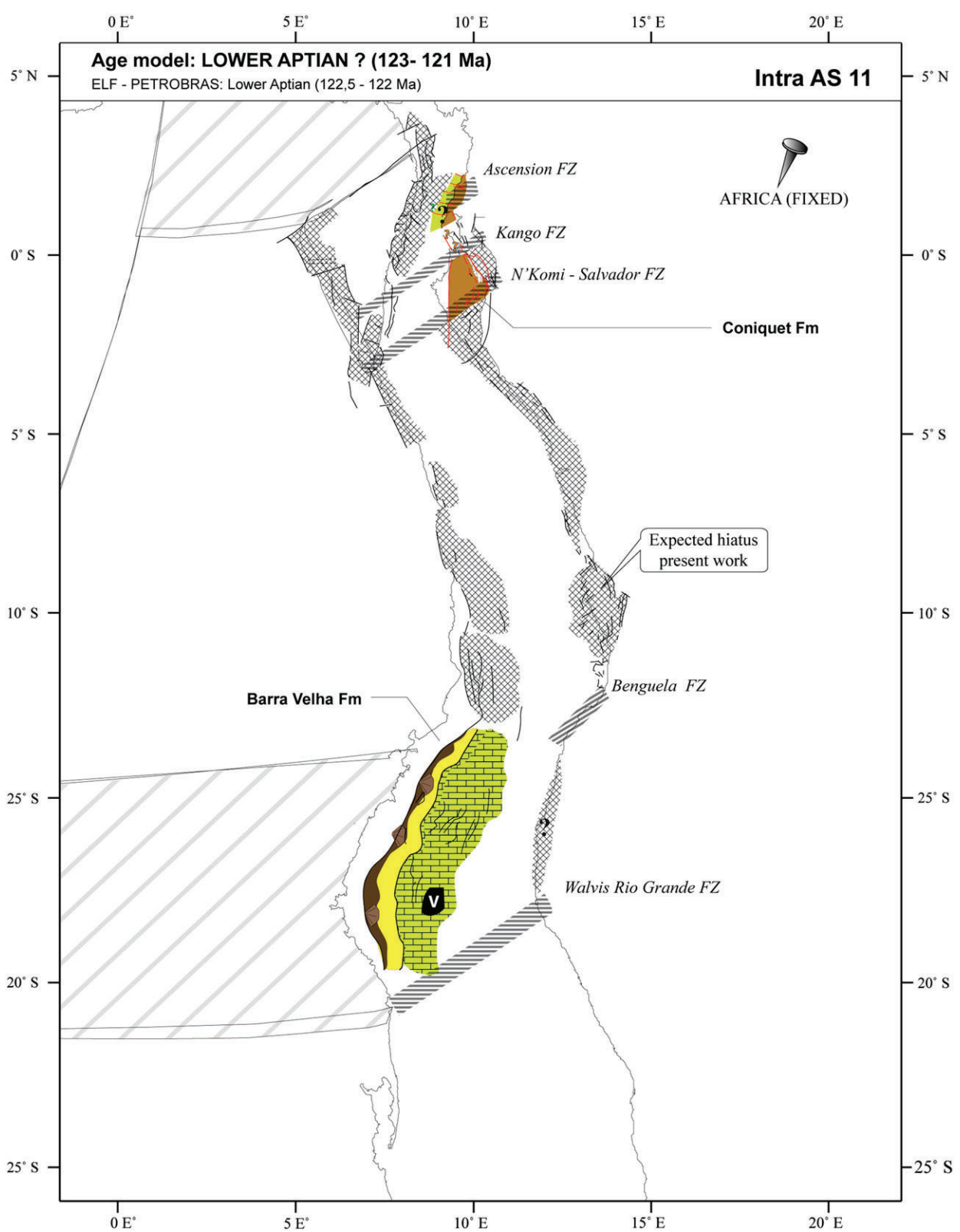


Fig. 12. Paleogeographic map at the Lower Aptian? (intra ostracode biozone AS11) – 123–121 Ma.

733 Sergipe–Alagoas Basins (Campos Neto et al., 2007). A proto-oceanic
 734 crust is expected at this time based on the geometrical relationship
 735 of the salt with the oceanic crust (see Petrobras charts, Milani et al.,
 736 2007 and Fig. 5).

6. Discussion: tectonic evolution

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

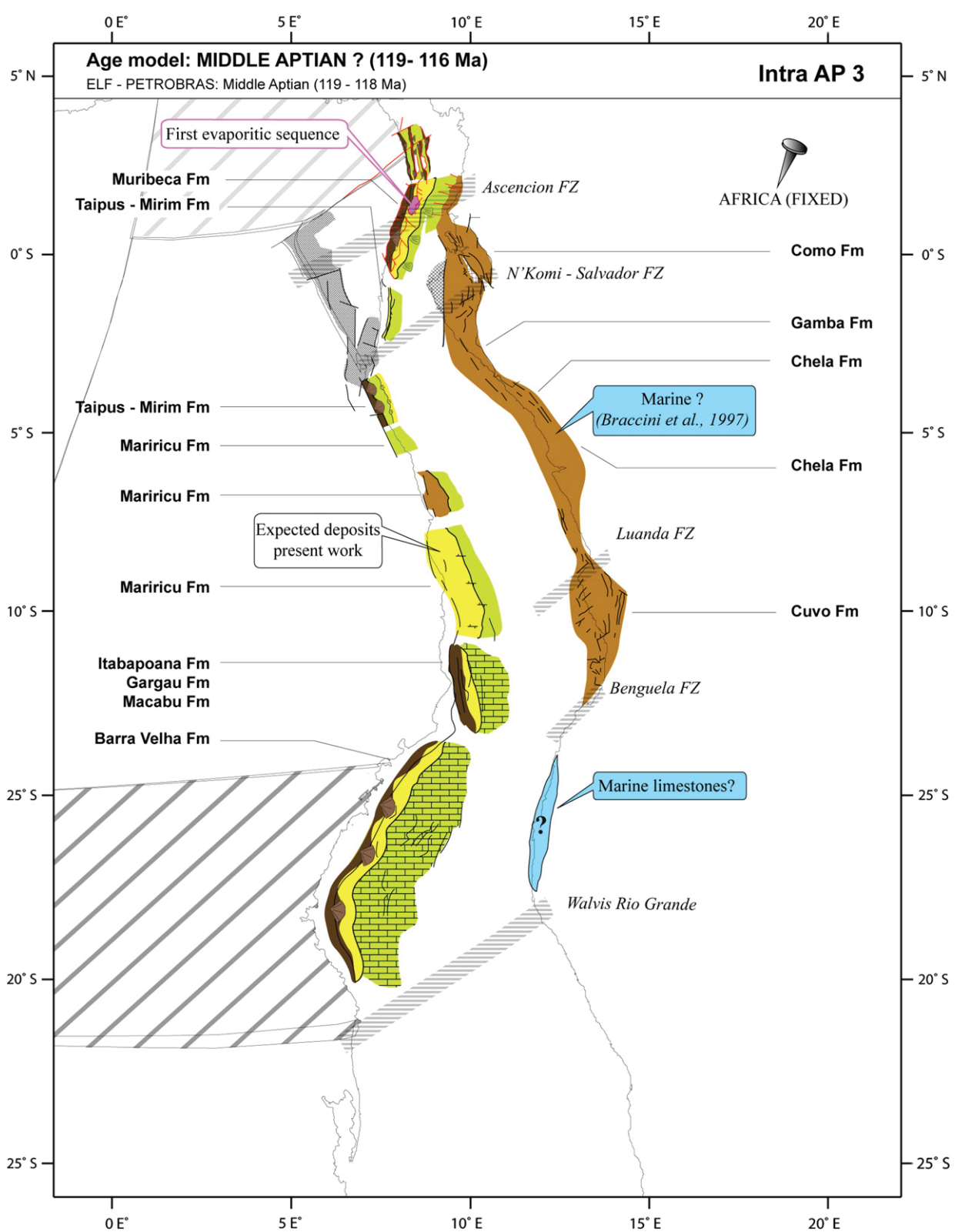


Fig. 13. Paleogeographic map at the Middle Aptian? (intra biozone AP3) — 119–116 Ma.

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

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

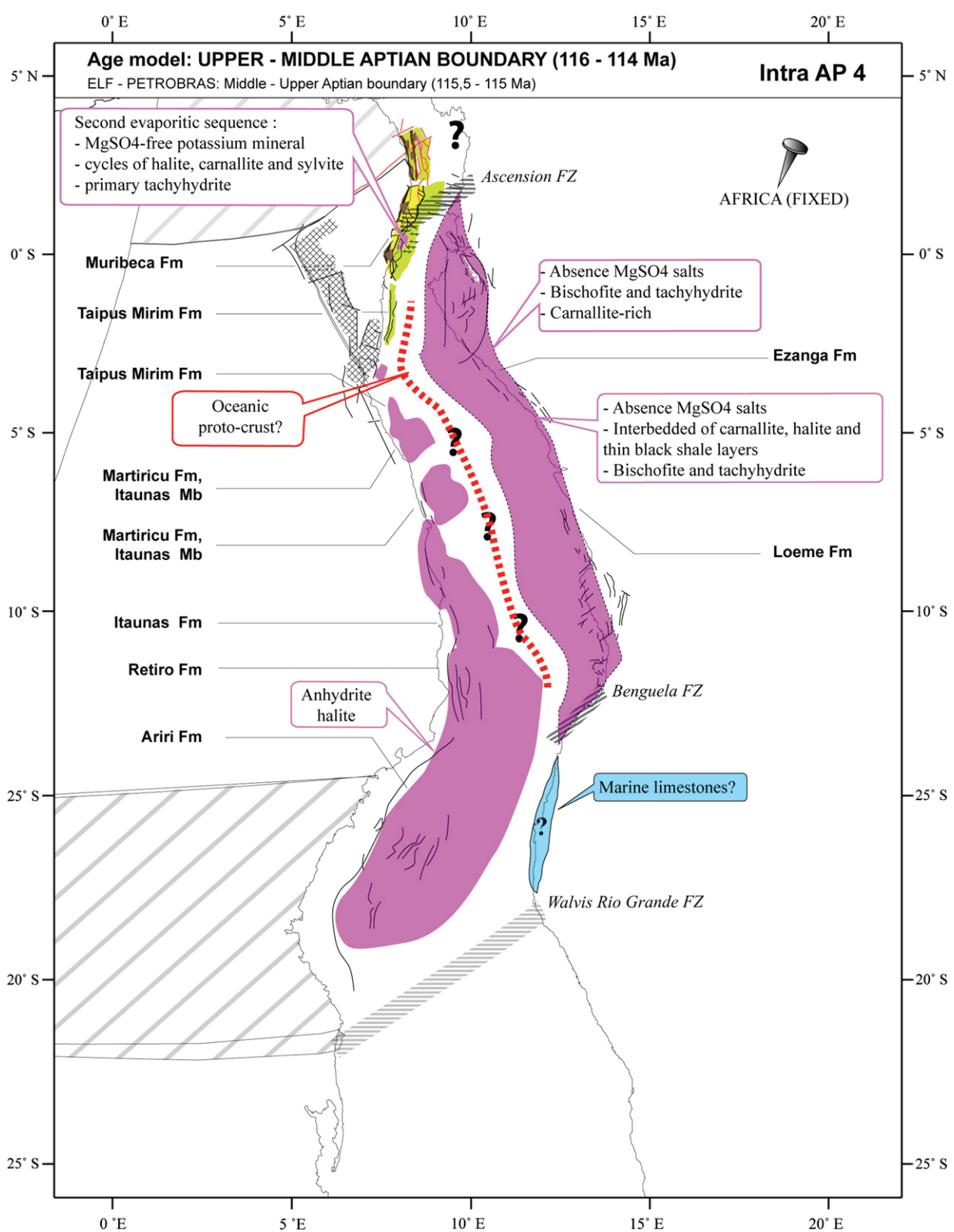


Fig. 14. Paleogeographic map at the Middle-Upper Aptian boundary (intra biozone AP4) – 116–114 Ma.

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

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

A

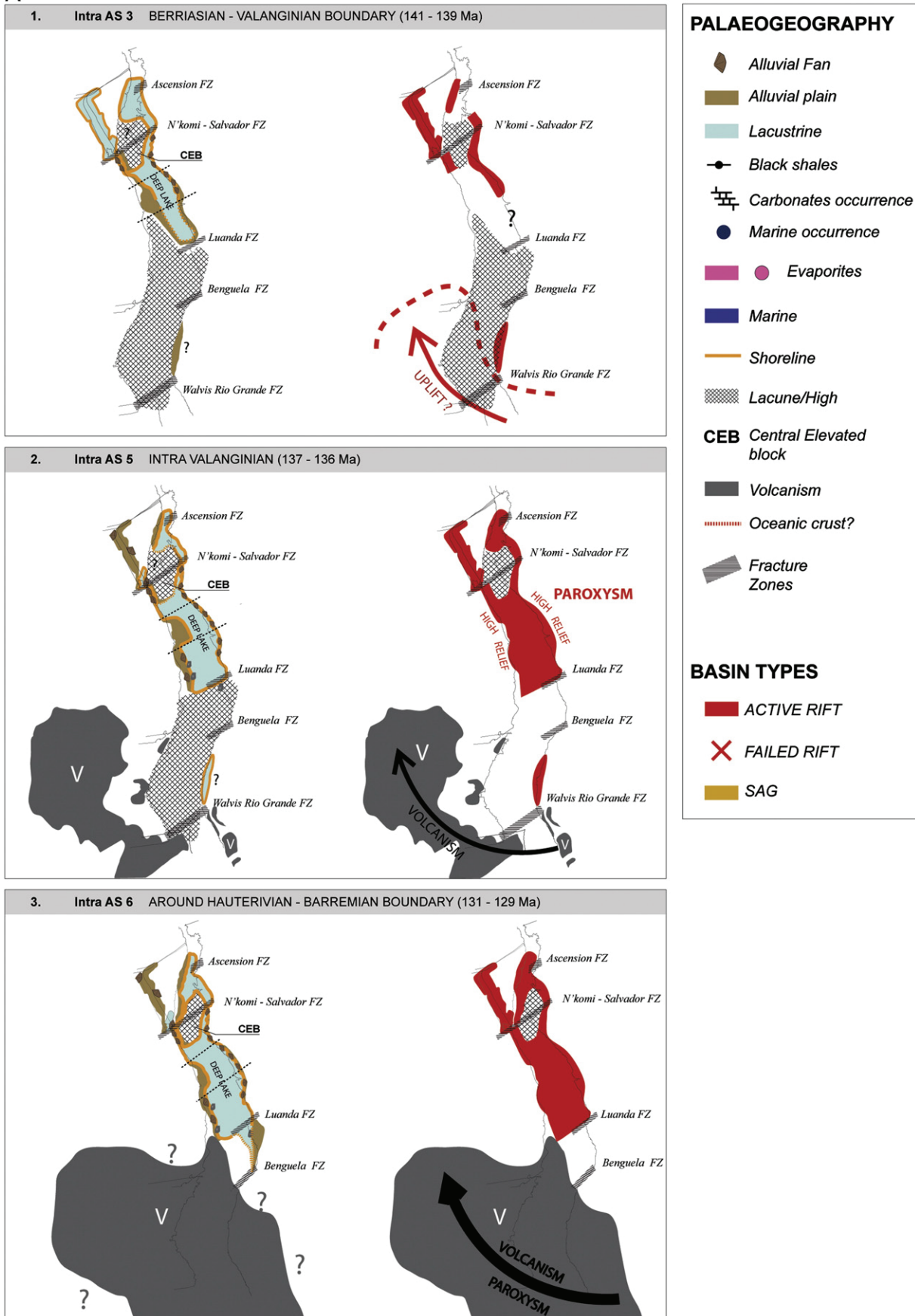
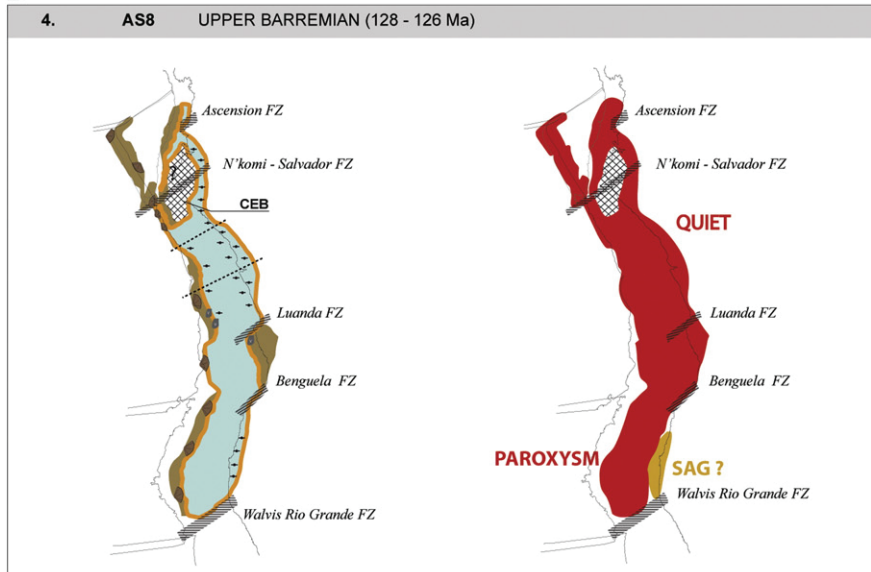


Fig. 15. Summary paleogeographic and geodynamic maps in eight stages from the Berriasian–Valanginian boundary (intra ostracode biozone AS3) to the Middle–Upper Aptian boundary (intra biozone AP4).

B



PALAEOGEOGRAPHY

- Alluvial Fan
- Alluvial plain
- Lacustrine
- Black shales
- Carbonates occurrence
- Marine occurrence
- Evaporites
- Marine
- Shoreline
- Lacune/High
- CEB** Central Elevated block
- Volcanism
- Oceanic crust?
- Fracture Zones

BASIN TYPES

- ACTIVE RIFT
- FAILED RIFT
- SAG

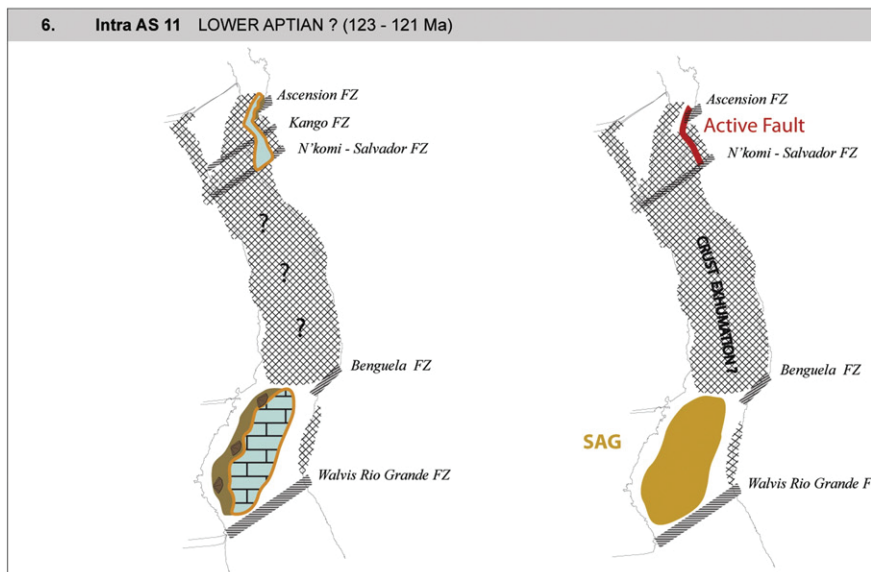
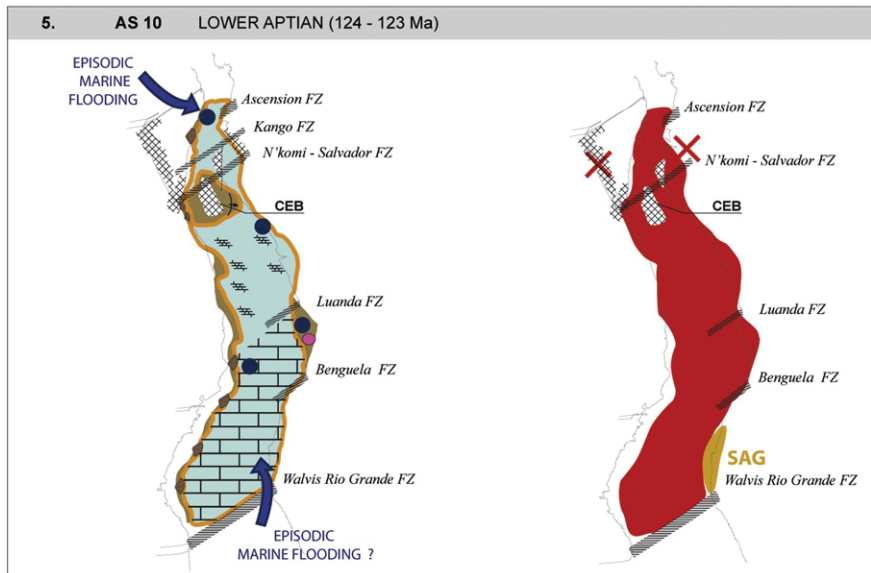


Fig. 15 (continued).

C

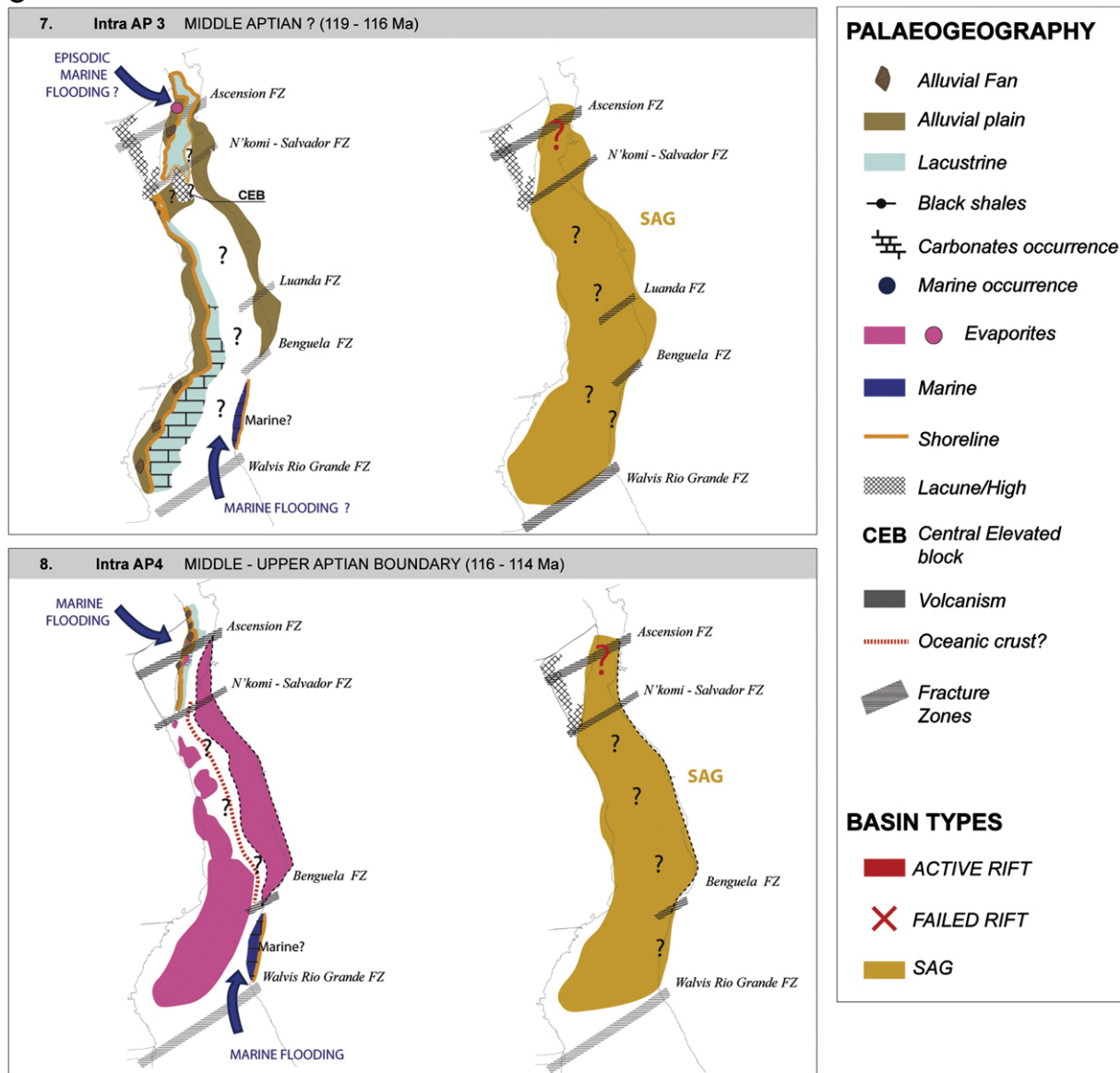


Fig. 15 (continued).

during biozones AS3 and part of AS4, i.e. during the end of the Berriasian and lowermost Valanginian (141–139 Ma). In the *southern domain*, south of the Benguela FZ, the lithosphere extension started at least after ostracode biozone O05 (= AS7), i.e. during the Early Barremian (130–128 Ma), but an extension contemporaneous of the basaltic floods of the Cabuinas and Camboriu Formations cannot be excluded (see discussion above). This means that the lithosphere extension of the central segment of the South Atlantic Ocean migrated southward from the Gabon and NE Brazil to southern Angola and southern Brazil (Santos Basin).

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

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

The sag phase corresponds to a thick wedge (Marton et al., 2000; Lentini et al., 2010) of sediments, unconformably overlapping the underlying sediments. Lentini's isopachs map shows a strong asymmetry between our northern and southern domain, with a mainly African sag in the north and a South American sag in the south and a transition between these two domains where sags occurred on both sides (Espírito Santo and Kwanza Basins). In spite of the poor 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 Brazilian side.

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

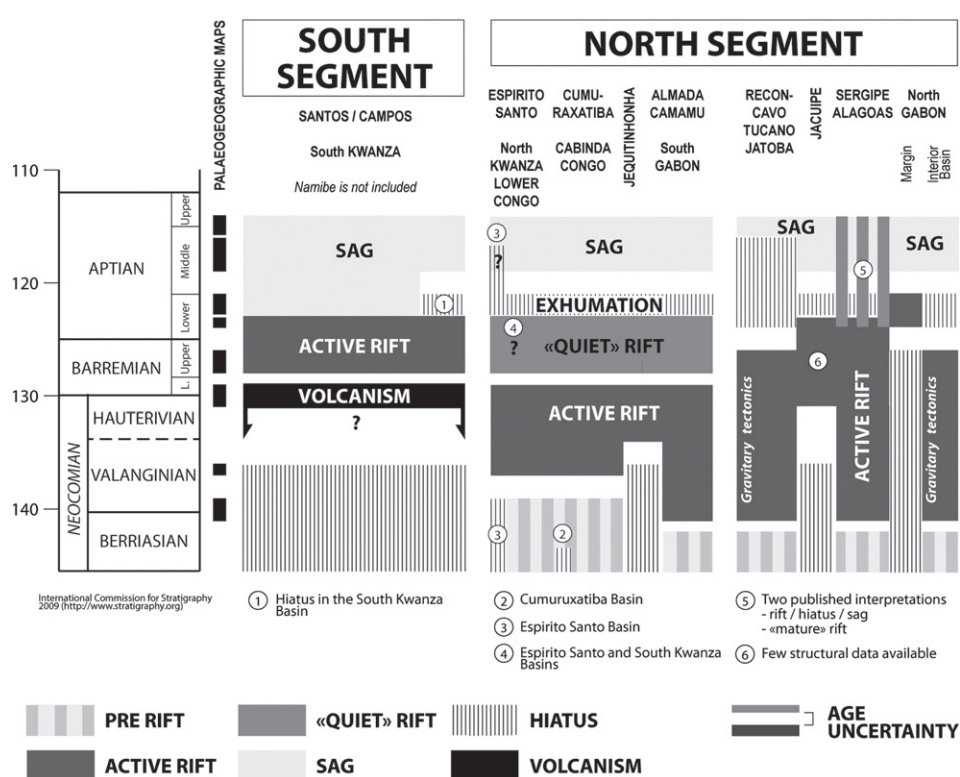


Fig. 16. Summary geodynamic chart of the evolution of the central segment of the South Atlantic Ocean based on the age model proposed in Fig. 3.

800 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
801 change of the structure of the lithosphere (Brun, 1999; Brun and Beslier, 1996).
802
803

804 7. Discussion: sedimentary and topographic evolution

805 7.1. Lake evolution

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

825 The two domains have a different lake evolution. The northern
826 one starts with deep lake deposits (Late Berriasian, AS3) becoming
827 more and more sandy (increase of the turbiditic supply, Valanginian,
828 AS5). This lake became progressively shallower and was filled by
829 deltas with high clinofolds (Upper Barremian–base Aptian, several
830 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 Jacuibe 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

848 7.2. Relief evolution

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

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

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

863 boundary (evaporites in the Kwanza Basin) and during the Early
864 Aptian (see below).

865 Two markers record the occurrence of *rift shoulders*: (1) alluvial
866 fans associated with active normal faults and (2) the nature of the
867 sediments and solutes coming from inland and preserved in the rift.

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

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

890 7.3. Marine floodings

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

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

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

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

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

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

951 8. Conclusion

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

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

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.

9. Uncited references

Dias et al., 1994
Pedreao and Lana, 2000
Uesugui, 1987

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