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Kinematics of the South Atlantic rift

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Abstract

The South Atlantic rift basin evolved as branch of a large Jurassic-Cretaceous intraplate rift zone between the African and South American plates during the final breakup of western Gondwana. While the relative motions between South America and Africa for post-breakup times are well resolved, many issues pertaining to the fit reconstruction and particular the relation between kinematics and lithosphere dynamics during pre-breakup remain unclear in currently published plate models. We have compiled and assimilated data from these intraplated rifts and constructed a revised plate kinematic model for the pre-breakup evolution of the South Atlantic. Based on structural restoration of the conjugate South Atlantic margins and intracontinental rift basins in Africa and South America, we achieve a tight fit reconstruction which eliminates the need for previously inferred large intracontinental shear zones, in particular in Patagonian South America. By quantitatively accounting for crustal deformation in the Central and West African rift zone, we have been able to indirectly construct the kinematic history of the pre-breakup evolution of the conjugate West African-Brazilian margins. Our model suggests a causal link between changes in extension direction and velocity during continental extension and the generation of marginal structures such as the enigmatic Pre-salt sag basin and the São Paulo High. We model an initial E–W directed extension between South America and Africa (fixed in present-day position) at very low extensional velocities until Upper Hauterivian times (≈ 126 Ma) when rift activity along in the equatorial Atlantic domain started to increase significantly. During this initial ≈ 17 Myr-long stretching episode the Pre-salt basin width on the conjugate Brazilian and West African margins is generated. An intermediate stage between 126.57 Ma and Base Aptian is characterised by strain localisation, rapid lithospheric weakening in the equatorial Atlantic domain, resulting in both progressively increasing extensional velocities as well as a significant rotation of the extension direction to NE–SW. From Base Aptian onwards diachronous lithospheric breakup occurred along the central South Atlantic rift, first in the Sergipe-Alagoas/Rio Muni margin segment in the northernmost South

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Atlantic. Final breakup between South America and Africa occurred in the conjugate Santos–Benguela margin segment at around 113Ma and in the Equatorial Atlantic domain between the Ghanaian Ridge and the Piauí-Ceará margin at 103Ma. We conclude that such a multi-velocity, multi-directional rift history exerts primary control on the evolution of this conjugate passive margins systems and can explain the first order tectonic structures along the South Atlantic and possibly other passive margins.

1 Introduction

The formation and evolution of rift basins and continental passive margins is strongly dependent on lithosphere rheology and strain rates (e.g. Buck et al., 1999; Bassi, 1995). Strain rates are directly related to the relative motions between larger, rigid lithospheric plates and thus the rules of plate tectonics. A consistent, independent kinematic framework for the pre-breakup deformation history of the South Atlantic rift allows to link changes in relative plate velocities and direction between the main lithospheric plates to events recorded at basin scale and might help to shed light on some of the enigmatic aspects of the conjugate margin formation in the South Atlantic, such as the Pre-salt sag basins along the West African margin (e.g. Huismans and Beaumont, 2011; Reston, 2010), the extinct Abimael ridge in the southern Santos basin, and the formation of the São Paulo high. Over the past decades, our knowledge of passive margin evolution and the sophistication of lithospheric deformation modelling codes has substantially increased (e.g. Huismans and Beaumont, 2011; Péron-Pinvidic and Manatschal, 2009; Rüpke et al., 2008; Crosby et al., 2008; Lavier and Manatschal, 2006), as have the accuracy and understanding of global and regional relative plate motion models (e.g. Seton et al., 2012; Müller et al., 2008) for oceanic areas. However, the connections between these two scales and the construction of quantified plate kinematic frameworks for pre-breakup lithospheric extension remains limited due to the fact that no equivalent of oceanic isochrons and fracture zones are generated during continental lithospheric extension to provide spatio-temporal constraints on the

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progression of extension. Provision of such kinematic frameworks would vastly help to improve our understanding of the spatio-temporal dynamics of continental margin formation. The South Atlantic basin with its conjugate South American and West African margins and associated Late Jurassic/Early Cretaceous rift structures (Fig. 1) offers an ideal testing ground to attempt to construct such a framework and link a kinematic model to observations from marginal and failed rift basins. There are relatively few major lithospheric plates involved, the motions between these plates during the early extension phase can modeled using well-documented intraplate rifts and the conjugate passive margins still exist in situ. In addition, an extensive body of published literature exists which documents detailed aspects of the conjugate passive margin architecture.

1.1 Aims and rationale

Following Reston (2010), the current state of previously published plate kinematic reconstructions of the South Atlantic rift has only been able to address basic questions related to the formation of the conjugate South Atlantic margins in pre-seafloor spreading times and falls short of explaining the impact of plate kinematic effects on rift margin evolution. In this paper, we present a completely revised plate kinematic model for the pre-breakup and early seafloor spreading history of the South Atlantic rift that integrates observations from all Major South American and African rifts. Our aim is to alleviate unnecessary complexity from existing plate tectonic models for the region – such as a number of large, inferred intracontinental shear zones, for which observational evidence is lacking – while providing a kinematic framework which can consistently explain relative plate motions between the larger lithospheric plates and smaller tectonic blocks. The model improves the full fit reconstruction between South American plates and Africa, especially in the southernmost South Atlantic and is able to explain the formation of the Salado and Colorado Basins in Argentina, two Early Cretaceous-aged basins which strike nearly orthogonal to the Main South Atlantic rift, in the context of larger scale plate motions. This allows us to link changes in plate motions with well-documented regional tectonic events recorded in basins along the Major rift systems

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and to explain the formation of the enigmatic Pre-salt sag basins of the central South Atlantic in the context of a multi-direction, multi-velocity plate kinematic history.

2 Plate reconstructions: data, regional elements, and methodology

Quantification of the spatio-temporal patterns of relative motions between rigid lithospheric plates based on the inventory of continental rifts, data from the conjugate passive margins and information from oceanic spreading in the South Atlantic allows us to construct a spatio-temporal framework for the pre-seafloor kinematics of continental rifting.

We utilise a combination of the interactive, open-source plate kinematic modelling software GPlates (<http://www.gplates.org>) as an intergration platform for our data and the Generic Mapping Tools (<http://gmt.soest.hawaii.edu>; Wessel and Smith, 1998) to generate our paleo-tectonic reconstructions (See Figs. 12–20 and electronic supplements).

2.1 Absolute plate motion model and timescale

The plate kinematic model is built on a hybrid absolute plate motion model which utilises a moving hotspot reference frame back to 100 Ma and an adjusted paleomagnetic absolute reference frame for times before 100 Ma (Torsvik et al., 2008). We are using the geomagnetic polarity timescale by Gee and Kent (2007, hereafter called *GeeK07*) which places anomaly M0 young at 120.6 Ma. The choice is based on an extensive review of global spreading velocities, in which an older age of M0y of 125.0 Ma (Gradstein et al., 2004) would result in excessive spreading velocities (Seton et al., 2009; Torsvik et al., 2009).

Global plate motion models are based on magnetic polarity timescales to temporarily constrain plate motions using seafloor spreading magnetic anomalies (e.g. Seton et al., 2012; Müller et al., 2008). In pre-seafloor spreading, continental environments,

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such well constrained direct age control for relative plate motions does not exist. Here, stratigraphic information from syn-rift sequences and subsidence data needs to be converted to absolute ages in a consistent framework. As the correlation between absolute ages and stratigraphic intervals has undergone several Major iterations over the past decades, published ages from South American and African rift basins require readjustment. To tie stratigraphic ages to the Magnetic polarity timescale predominantly used for global plate kinematic models, we have converted the estimates given by Gradstein et al. (1994, here named *Geek07/G94*) and Gradstein et al. (2004, *Geek07/GTS04*) to the *Geek07* polarity chron ages (Fig. 2). We use *Geek07/GTS04*, which places Base Aptian (Base M0r old) at 121 Ma (Fig. 2).

For published data we have attempted to convert both, stratigraphic and numerical ages to the new hybrid timescale where possible. One particular example for such large differences in absolute ages are the publications by Genik (1992, 1993) which are based on the EXXON 1988 timescale (Fig. 2; Haq et al., 1987). Here, the Base Cretaceous is given as ≈ 133 Ma, whereas the recent GTS timescales (Gradstein et al., 2004) as well as our hybrid timescale place the Base Cretaceous between 144.2 ± 2.5 and 142.42 Ma, respectively. Naturally, issues pertaining to correlate biostratigraphic zonation across different basins further complicate the conversion between stratigraphic and absolute ages regionally (e.g. Poropat and Colin, 2012; Chaboureau et al., in press).

2.2 Continental intraplate deformation

Deformation between rigid continental plates has to adhere to the basic rules of plate tectonics and can be expressed as relative rotations between a conjugate plate pair for any given time (Dunbar and Sawyer, 1987). Depending on data coverage and quality, a hierarchical plate model can be assembled from this information (e.g. Ross and Scotese, 1988). In pre-seafloor spreading environments, the quantification of horizontal deformation on regional scale is complicated as discrete time markers such as oceanic magnetic anomalies or clear structural features, such as oceanic fracture

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zones, are lacking. However, rift infill, faulting and post rift subsidence allow – within reasonable bounds – to quantify the amount of horizontal deformation (White, 1989; Gibbs, 1984, 1983; Sclater and Christie, 1980; McKenzie, 1978). We assume that significant amounts of horizontal displacement (>15 km) are preserved in the geological record either as foldbelts (positive topographic features) or fault-bounded sedimentary basins and recognised subsequently. Key elements of our plate kinematic model are a set of lithospheric blocks which are non-deforming during the rifting and breakup of western Gondwana (160–85 Ma; Fig. 1). These blocks were delineated using first order structures, such as main basin-bounding faults, thrust belts or large gradients in reported sediment thickness, indicative of subsurface faulting, in conjunction with potential field data and publications. We then constructed a relative plate motion model by carefully reviewing published data to constrain the timing, direction, and accumulated strain in intraplate deformation zones. This information was augmented with interpreted tectonic lineaments and kinematic indicators (faults, strike slip zones) from various publications (e.g. Exxon Production Research Company, 1985; Matos, 1992, 2000; Genik, 1992, 1993) as well as potential field data from publicly available sources (Andersen et al., 2010; Sandwell and Smith, 2009; Maus et al., 2007) to further refine rigid block outlines. Stage rotations were derived by identifying the predominant structural grain and choosing an appropriate rotation pole which allowed plate motions to occur orthogonal to the Main extensional or compressional structures. The amount of relative horizontal displacement was then implemented by visual fitting, using published data.

Estimates for extension along some sections were verified by structural balancing. Due to the inherent lack of precise kinematic and temporal markers during continental deformation and insufficient data we only describe continental deformation by a single stage rotation (Table 1, Figs. 5 and 6).

2.3 Passive margins and oceanic domain

Over the past decade, a wealth of crustal-scale seismic data covering the conjugate South Atlantic margins, both from industry and academic projects, have been published

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(e.g. Blauch et al., 2011; Unternehr et al., 2010; Blauch et al., 2009, 2008; Greenroyd et al., 2007; Franke et al., 2007, 2006; Contrucci et al., 2004; Mohriak, 2003; Mohriak and Rosendahl, 2003; Meisling et al., 2001; Cainelli and Mohriak, 1999; Rosendahl and Groschel-Becker, 1999). Where possible, we made use of these data to redefine the location of the continent-ocean boundary in conjunction with proprietary industry long offset reflection seismic data (such as the ION GXT CongoSPAN lines, http://www.iongeo.com/Data_Library/Africa/CongoSPAN/) as well as proprietary and public potential field data and models (e.g. Sandwell and Smith, 2009; Maus et al., 2007).

As some segments of this conjugate passive margin system show evidence for hyperextended margins, we introduce the “landward limit of the oceanic crust” (LaLOC) as boundary which delimits relatively homogeneous oceanic crust oceanward from either extended continental crust or exhumed continental lithospheric mantle landward where an interpretation of the Moho is not possible. This definition has proven to be useful in areas where a classic continent-ocean boundary (COB) cannot easily be defined such as in the distal parts of the Kwanza basin offshore Angola (Unternehr et al., 2010) or along the oceanward boundary of the Santos basin (Zalán et al., 2011).

Area balancing of the Top Basement and Moho horizons has been used on published passive margin cross sections by Blauch et al. (2011) to restore the initial pre-deformation stage of the margin, assuming no out-of-plane motions and constant area. While these assumptions simplify the actual margin architecture and do not account for alteration of crustal thickness during extension, Fig. 3 shows that the differences between a choice of three different limits of the extent of continental crust (minimum, COB based on Blauch et al., 2011, and LaLOC) only has relatively limited effects on the width of the restored margin.

Considering the plate-scale approach of this study and inherent uncertainties in the interpretation of subsalt structures on seismic data, we believe that these estimates provide valid tie points for a fit reconstruction. The resulting fit matches well with Chang et al. (1992)’s estimates for pre-extensional margin geometry for the Brazilian margin. In addition, we carried out an extensive regional interpretation of Moho, Top Basement

and Base Salt reflectors on ION GXT CongoSPAN seismic data to verify results from areal balancing of the published data.

Published stratigraphic data from the margins was used to better constrain the onset and dynamics of rifting along with possible extensional phases (e.g. Karner and Gambôa, 2007). Little publicly available data from distal and deeper parts of the margins exist which could help to determine the spatio-temporal patterns of the earliest synrift subsidence.

To quantify oceanic spreading and relative plate motions between the South American and Southern African plates before the Cretaceous Normal Polarity Superchron (CNPS, 83.5–120.6 Ma) we use a pick database compiled by the EarthByte Group at the University of Sydney, forming the base for the digital ocean floor age grid (Müller et al., 2008; Seton et al., 2012).

We have combined this data with the interpretations of Max et al. (1999) and Moulin et al. (2009) and the WDMAM gridded magnetic data (Maus et al., 2007) to create a set of isochrons for anomaly chrons M4 old (126.57 Ma), M2 old (124.05 Ma), and M0r young (120.6 Ma) using the magnetic polarity timescale of Gee and Kent (2007). M sequence anomalies from M11 to M8 are only reported for the African side (Rabinowitz and LaBrecque, 1979). M7 has been identified on both conjugate abyssal plains closed to the COB (Moulin et al., 2009; Rabinowitz and LaBrecque, 1979). However, due to limited amount of picks for anomalies older than M4 and significant breakup-related volcanic activity in the southern South Atlantic (Franke et al., 2010; Blaich et al., 2009; Gladchenko et al., 1998) we use anomaly M4n old as our oldest oceanic isochron to constrain the motion of South America relative to Africa. Oceanic spreading and relative plate velocities during the CNPS are linearly interpolated with plate motion paths only being adjusted to follow prominent fracture zones in the Equatorial and South Atlantic.

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3 Tectonic elements: rigid blocks and deforming domains

Burke and Dewey (1974) reported that the African plate did not behave as single rigid plate during the Cretaceous period, highlighting the importance of incorporating intraplate deformation in plate tectonic reconstructions. Recent plate models for the South Atlantic region now subdivide the present-day South American and African continental plates into a number of lithospheric sub-plates (e.g. Moulin et al., 2009; Torsvik et al., 2009; Eagles, 2007; Macdonald et al., 2003; Unternehr et al., 1988; Fairhead, 1988; Pindell and Dewey, 1982; Martin et al., 1981) which are assumed to have behaved near-rigidly during the Late Jurassic to Mid Cretaceous times. These sub-plates are defined prior to break-up by four Major plate boundary zones and extensional domains: the Central African (CARS), West African (WARS), South Atlantic (SARS), and Equatorial Atlantic Rift Systems (EqRS). We here include the “Patagonian extensional domain” and related smaller rift structures in southern South America in our definition of the SARS (Fig 1). From these four extensional domains, only the SARS and EqRS transitioned from rifting to break up, creating the Equatorial and South Atlantic ocean basins. We review timing, kinematics, type and amount of deformation for each of these domains.

3.1 Africa

The West African and Central African rift systems (Figs. 1 and 4; WARS & CARS) and associated depocenters document extensional deformation between the following continental lithospheric sub-plates in Africa starting in the Latest Jurassic/Early Cretaceous:

1. Northwest Africa (NWA), bounded to the East by the WARS/East Niger Rift and delimited by the Central and Equatorial Atlantic continental margins to the West and South, respectively (Guiraud et al., 2005; Burke et al., 2003; Janssen et al., 1995; Genik, 1993, 1992; Guiraud et al., 1992; Fairhead, 1988, 1986; Schull,

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1988; Reeves et al., 1987; Bermingham et al., 1983; Browne and Fairhead, 1983; Burke and Dewey, 1974).

2. Nubian/Northeast Africa (NEA), bounded by the WARS to the West, and the CARS/Central African Shear Zone to the South (Genik, 1993; Bosworth, 1992; Genik, 1992; Fairhead and Binks, 1991; Fairhead, 1988; Popoff, 1988; Schull, 1988; Browne et al., 1985; Browne and Fairhead, 1983). To the East, Northeast and North this block is delimited by the East African rift, the Red Sea and the Mediterranean margin, respectively.
3. Southern Africa (SAf) is separated from NEA through the CARS and bounded by the East African Rift system to the East and Southeast. Its southern and western margins are defined by the South Atlantic continental passive margins (e.g. Nürnberg and Müller, 1991; Unternehr et al., 1988).
4. The Jos subplate, named after the Jos Plateau in Nigeria, is situated between NWA, NEA and the Benoue Trough region. It is delimited along its western margin by a graben system of Early Cretaceous age in the Gao Trough/Graben area in Mali and the Bida/Nupe basin in NW Nigeria (Guiraud et al., 2005; Genik, 1993; Guiraud and Maurin, 1992; Genik, 1992; Adeniyi, 1984; Cratchley et al., 1984; Wright, 1968). The Benoue Trough and WARS delimit the the Jos subplate to the South and East. As northern limit we chose a diffuse boundary zone through the lullemeden/Sokoto Basin and Air Massive, linking the WARS with the Gao Trough area (Guiraud et al., 2005; Genik, 1993; Guiraud and Maurin, 1992; Genik, 1992; Cratchley et al., 1984).
5. The Adamaoua and Bongor blocks are situated south of the Benoue Trough and north of the dextral Borogop fault zone. This fault zone defines the western end of the CARS as it enters the Adamaoua region of Cameroon (Genik, 1993, 1992; Benkhelil, 1982; Burke and Dewey, 1974). Together with the Benoue Trough in the north, the Atlantic margin in the west and the Doba, Bongor, Bormu-Massenyia

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basins it encompasses a relatively small cratonic region in Nigeria/Cameroon which has been termed “Benoue Subplate” by previous workers (e.g. Moulin et al., 2009; Torsvik et al., 2009). The Yola rift branch (YB in Fig. 1) of the Benoue Trough indicates significant crustal thinning (Stuart et al., 1985) justifying a subdivision of this region into the two blocks.

The CARS and WARS are distinct from earlier Karoo-aged rift systems which mainly affected the eastern and southern parts Africa (Bumby and Guiraud, 2005; Catuneanu et al., 2005) but have presumably formed along pre-existing older tectonic lineaments of Panafrican age (Daly et al., 1989).

3.1.1 Central African Rift System (CARS)

The eastern part of the CARS, consisting of the Sudanese Melut, Muglad and Bagarra basins, forms a zone a few hundred kilometers wide with localised NW–SE striking sedimentary basins which are sharply delimited to the north by the so-called Central African Shear Zone (Bosworth, 1992; McHargue et al., 1992; Schull, 1988; Exxon Production Research Company, 1985; Browne and Fairhead, 1983). Subsurface structures indicate NNW/NW-trending main basin-bounding lineaments and crustal thinning with up to 13 km of Late Jurassic/Early Cretaceous-Tertiary sediments (Fig. 4; Browne and Fairhead, 1983; Browne et al., 1985; Schull, 1988; McHargue et al., 1992; Mohamed et al., 2001). Published values for crustal extension in the Muglad and Melut basins in Sudan range between 15–27 km (McHargue et al., 1992) in SW–NE direction and $\beta = 1.61$ for an initial crustal thickness of 35 km, resulting in 56 km of extension (Mohamed et al., 2001) with a first postrift phase commencing in the Albian (≈ 110 Ma; McHargue et al., 1992).

Dextral transtensional motions along the western part of the CARS during the Early Cretaceous created the Salamat, Doseo and Doba basins (Fig. 4; Schull, 1988; Bosworth, 1992; McHargue et al., 1992). These depocenters locally contain more than 8 km of Early Cretaceous to Tertiary sediments and are bound by steeply dipping faults,

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indicative of pull-apart/transensional kinematics for the basin opening (Fig. 4; Genik, 1993; Maurin and Guiraud, 1993; Binks and Fairhead, 1992; Guiraud et al., 1992; Genik, 1992; Exxon Production Research Company, 1985; Browne and Fairhead, 1983). The structural inventory of these basins largely follows old Pan-African aged lineaments and has been reactivated during the Santonian compressive event (Guiraud et al., 2005; Janssen et al., 1995; Maurin and Guiraud, 1993; Genik, 1992; Daly et al., 1989).

The Borogop Fault defines the western part of the Central African Shear Zone and enters the cratonic area of the Adamaoua uplift in Cameroon, where smaller, Early Cretaceous-aged basins such as the Ngaoundere Rift are located (Fig. 4; Fairhead and Binks, 1991; Guiraud et al., 1992; Maurin and Guiraud, 1993; Plomerová et al., 1993). The reported total dextral displacement is estimated to be 35–40 km in the Doseo Basins (Genik, 1992; Daly et al., 1989), which is in accordance with the 25–56 km extension reported from the Sudanese basins (McHargue et al., 1992; Mohamed et al., 2001).

We have implemented a total extension of 35 km between 143 and 110 Ma (Early Albian) in the northern Muglad Basin, generated through rotation of the SAf block counterclockwise relative to NEA around a rotation pole in the southern Muglad basin (Fig. 5). This stage pole location results in compression in the Anza Trough in Kenya which is supported by observations of subsurface reverse faulting of Early Cretaceous age (Reeves et al., 1987). Stage poles and associated small circles for the NEA–SAf rotation are oriented orthogonally to mapped Early Cretaceous extensional fault trends for the Doba and Doseo Basin (Genik, 1992), and graben-bounding normal faults in the Sudanese basins (Fig. 5). Other authors have used 70 km of strike slip/extension for the CASZ and Sudan Basins, respectively (Moulin et al., 2009), which is about double the amount reported (Genik, 1992; McHargue et al., 1992). Torsvik et al. (2009) model the CARS but do not specify an exact amount of displacement between their Southern African and the NE African sub-plates.

3.1.2 West African Rift System (WARS)

The West African/East Niger rift (WARS) extends northward from the eastern Benoue Trough region through Chad and Niger towards southern Algeria and Lybia (Fig. 1). The recent Chad basin is underlain by a series of N–S trending rift basins, encompassing the Termit Trough, N'Dgel Edgi, Tefidet, Ténéré, and Grein-Kafra Basins containing up to 12 km of Early Cretaceous to Tertiary sediments (Fig. 4; Guiraud et al., 2005; Guiraud and Maurin, 1992; Genik, 1992; Exxon Production Research Company, 1985). These basins are extensional, asymmetric rifts, initiated through block faulting in the Early Cretaceous, with a dextral strike-slip component reported from the Tefidet region (“Tef” in Fig. 1; Guiraud and Maurin, 1992; Genik, 1992). The infill is minor Paleozoic to Jurassic pre-rift, non-marine sediments and a succession of non-marine to marine Cretaceous clastics of up to 6 km thickness with reactivation of the structures during the Santonian (Guiraud et al., 2005; Genik, 1992; Bumby and Guiraud, 2005). Towards the north of the WARS, N–S striking fault zones of the El Biod-Gassi Touil High in the Algerian Sahara and associated sediments indicate sinistral transpression during the Early Cretaceous (Guiraud and Maurin, 1992). The main rift development occurred during Genik (1992)’s Phase 3 from the Early Cretaceous to Top Albian (130–98 Ma) with full rift development by 108 Ma (Genik, 1992, using the EXXON timescale).

Early Cretaceous sedimentation and normal faulting in the lullemeden/Sokoto and Bida Basins in NW Nigeria and the Gao Trough in Mali indicates that lithospheric extension also affected an area NW of the Jos subplate and further west of the WARS sensu strictu (Guiraud et al., 2005; Obaje et al., 2004; Genik, 1993; Guiraud and Maurin, 1992; Genik, 1992; Cratchley et al., 1984; Adeniyi, 1984; Petters, 1981; Wright, 1968). Reported sediment thicknesses here range between 3–3.5 km for the Bida Basin (Obaje et al., 2004, Fig. 4). Our definition of the WARS hence encompasses this area of diffuse lithospheric extension.

Palinspastic restoration of 2-D seismic profiles across the Termit basin part of the WARS yield extension estimates between 40–80 km based (using Moho depths of

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26 km; Genik, 1992). We have done basic area balancing using an unstretched crustal thickness of 39 and 40 km (assuming no out-of plane motions) along Profile F-F' of Genik (1992, his Fig. 9), resulting in a maximum cumulative extension of 90–100 km. Here, however, the Moho geometry is only given in the central part of the cross section hence introducing large uncertainties in the total amount of extension. We use 70 km of extension in the Termit Basin region and 60 km in the Grein-Kafra Basin to accommodate relative motions between the Jos Subplate and NEA between Base Cretaceous and 110 Ma. Fault and sediment isopach trends indicate an E–W to slightly oblique rifting, trending NNW–SSE for the main branch of the WARS. Our stage rotation between NWA and NEA results oblique, NNE–SSW directed opening of the WARS (Fig. 6). Other workers have used 130 km of E–W directed extension in the South (Termit Basin) and 75 km for northern parts (Grein/Kafra Basins; Torsvik et al., 2009) between 132–84 Ma or 80 km of SW–NE directed oblique extension (Moulin et al., 2009). For the Bida (Nupe) Basin/Gao Trough, we estimate that approximately 15 km of extension occurred between the Jos Subplate and NWA, resulting in a cumulative extension between NWA and NEA of 85–75 km between 143 Ma and 110 Ma.

3.1.3 Benoue Trough

The Benoue Trough and associated basins like the Gongola Trough, Bornu and Yola Basins are located in the convergence of the WARS and CARS in the junction between the Northwest, Northeast and Southern African plates. The tectonic position makes the Benoue Trough susceptible to changes in the regional stress field, reflected by a complex structural inventory (Benkheilil, 1989; Popoff, 1988). Sediment thicknesses reach locally more than 10 km along, with the oldest outcropping sediments reported as Albian age from anticlines in the Upper Benoue Trough (Fairhead and Okereke, 1990; Benkheilil, 1989). Subsidence in the Benoue Trough commences during Late Jurassic to Barrêmian as documented by the Bima-1 formation in the Upper Benoue Trough (Guiraud et al., 2005; Guiraud and Maurin, 1992).

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The observed sinistral transtension in the Benoue Trough is linked to the opening of the South Atlantic basin and extension in the WARS and CARS (Guiraud et al., 2005; Genik, 1993, 1992; Fairhead and Binks, 1991; Fairhead and Okereke, 1990; Benkhelil, 1989; Popoff, 1988; Benkhelil, 1982; Burke, 1976; Burke and Dewey, 1974). It follows that the onset of rifting and amount of extension in the Benoue Trough is largely controlled by the relative motions along the WARS and CARS. Maximum crustal extension estimates based in gravity inversion are 95 km, 65 km, and 55 km in the Benue and Gongola Troughs, and Yola Rift with about 60 km of sinistral strike slip (Fairhead and Okereke, 1990; Benkhelil, 1989). Rift activity is reported from the “Aptian (or earlier)” to the Santonian (Fairhead and Okereke, 1990), synchronous with the evolution of the CARS and WARS (Guiraud et al., 2005; Genik, 1992).

We here regard the Benoue Trough as product of differential motions between NWA, NEA and SAf. Deformation implemented in our model for the WARS and CARS result in ≈ 20 km of N–S directed relative extension and about 50 km of sinistral strike-slip in the Benoue Trough between the Early Cretaceous and lower Albian.

3.2 South America

The present-day South American continent is composed of a set of Archean and Proterozoic cores which were assembled until the early Paleozoic, with its southernmost extent defined by the Rio de la Plata craton (Fig. 7; Almeida et al., 2000; Pángaro and Ramos, 2012). Large parts of South America, in contrast to Africa, show little evidence for significant and well preserved, large offset (10’s of km) intraplate crustal deformation during the Late Jurassic to Mid-Cretaceous. In the region extending from the Guyana shield region in the north, through Amazonia and São Francisco down to the Rio de la Plata Craton there are no clearly identifiable sedimentary basins or compressional structures with significant deformation reported in the literature which initiated or became reactivated during this time interval.

The Amazon basin and the Transbrasiliano Lineament have been used as the two major structural elements by various authors to accommodate intraplate deformation of

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the main South American plate. Eagles (2007) suggests the Solimões-Amazon-Marajó basins as location of a temporary, transpressional plate boundary during South and Equatorial Atlantic rifting, where a southern South America block is dextrally displaced by ≈ 200 km against a northern block. The basin is underlain by old lithosphere of the Amazonia Craton (Li et al., 2008; Almeida et al., 2000) which experienced one main rifting phase in early Paleozoic times and subsequent, predominantly Paleozoic sedimentary infill (Fig. 7; Nunn and Aires, 1988; Matos and Brown, 1992; Gonzaga et al., 2000; da Cruz Cunha et al., 2007). It is covered by a thin blanket of Mesozoic and Cenozoic sediments which show mild reactivation with NE-trending reverse faults and minor dextral wrenching along its eastern margin/Foz do Amazon/Marajó Basin during the Late Jurassic to Early Cretaceous (da Cruz Cunha et al., 2007; Costa et al., 2001; Gonzaga et al., 2000). Reactivation affecting the whole Amazon basin is reported only from the Cenozoic (Costa et al., 2001; Azevedo, 1991). We do not regard this tectonic element as a temporary plate boundary during formation of the South Atlantic.

The continental-scale Transbrasiliano lineament (TBL; Almeida et al., 2000) formed during the Pan-African/Brasiliano orogenic cycle. It is a potential candidate for a Major accommodation zone for intraplate deformation in South America (Pérez-Gussinyé et al., 2007; Feng et al., 2007), however, the amount of accommodated deformation and the exact timing remain elusive (Almeida et al., 2000). Some authors suggest strike slip motion along during the opening of the South Atlantic between 60–100 km along this 3000 km long, continent-wide shear zone, reaching from NE Brazil down into northern Argentina (Aslanian and Moulin, 2010; Moulin et al., 2009; Fairhead et al., 2007). Along undulating lineaments such as the TBL, any strike-slip motion would have resulted in a succession of restraining and releasing bends (Mann, 2007), creating either compressional or extensional structures in the geological record. For comparison, the reported offset along the Borogop Shear zone in the Central African Rift System ranges around 40 km during the late Jurassic–Early Cretaceous and created a series of deep (>6 km) intracontinental basins (Doba, Doseo, Salamat – Fig. 4; Genik, 1992; McHargue et al., 1992). While we do not refute evidence of reactivation of the TBL during the opening

of the South Atlantic, published geological and geophysical data do not provide convincing support for the existence of a plate boundary separating the South American platform along the Transbrasiliano lineament during the opening of the South Atlantic.

In southern Brazil, previous authors have argued for the Carboniferous Paraná Basin being the location for a large NW–SE striking intracontinental shear zone to close the “underfit” problems in the southern part of the South Atlantic (Moulin et al., 2012, 2009; Torsvik et al., 2009; Eagles, 2007; Nürnberg and Müller, 1991; Unternehr et al., 1988; Sibuet et al., 1984). This zone, obscured by one of the largest continental flood basalt provinces in the world (Peate, 1997; White and McKenzie, 1989), has been characterised as R-R-R triple junction with 100 km N–S extension (Sibuet et al., 1984), as Paraná-Cochabamba shear zone with 150 km dextral offset (Unternehr et al., 1988), as Parana-Chacos Deformation Zone with 60–70 km extension and 20–30 km of strike slip (Nürnberg and Müller, 1991), as Paraná-Etendeka Fracture Zone – a transtensional boundary with 175 km lateral offset (Torsvik et al., 2009), or dextral strike-slip zone with 150 km strike slip and 70 km extension (Moulin et al., 2009). Peate (1997) ruled out the possibility for a R-R-R triple junction due to timing of magma emplacement and orientation of the associated dyke swarm. The minimum amount of deformation proposed by previous authors is 20–30 km strike slip and 60–70 km extension (Nürnberg and Müller, 1991). In analogy to the well documented CARS and the discussion of the TBL above, such significant displacement should have resulted in a set of prominent basins extending well beyond the cover of the Paraná flood basalt province and manifested itself as major break along the South American continental margin, similar to the Colorado and Salado basins further south. Although sub-basalt basin structures have been reported (Eyles and Eyles, 1993; Exxon Production Research Company, 1985), there is no evidence for a large scale continental shear zone obscured by the Paraná large igneous province (LIP).

In our model we have subdivided the present-day South American continent in the following tectonic blocks, partly following previous authors (Fig. 1; e.g. Unternehr et al.,

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1988; Nürnberg and Müller, 1991; Macdonald et al., 2003; Torsvik et al., 2009; Moulin et al., 2009):

1. The main South American Platform (SAm), extending from the Guyana Craton in the North to the Rio de la Plata Craton in the South, with the exception of the NE Brazilian Borborema Province.
2. The NE Brazilian Borborema Province block (BPB).
3. The Salado Subplate, located between the Salado and Colorado Basins.
4. A *Patagonian extensional domain* south of the Colorado Basin, composed of the rigid Pampean Terrane, North Patagonian Massif, Rawson block, San Julian block, the Deseado block, and Malvinas/Falkland block, and the Maurice Ewing Bank extended continental crust.

3.2.1 Northeast Brazil

The Borborema Province block (BPB; Figs. 1 and 7) is located in NE Brazil and separated from the South American plate along a N–S trending zone extending from the Potiguar Basin on the eastern Brazilian Equatorial Atlantic margin southwards to the Recôncavo-Tucano-Jatobá rift (RTJ, Fig. 7). It is an exception in the otherwise tectonically stable South American plate and a set of isolated Early Cretaceous rift basins (e.g. Araripe and Rio do Peixe basins) as well as abundant evidence of reactivated Proterozoic aged basement structures and shear zones indicates distributed, but highly localised lithospheric deformation during the opening of the South Atlantic rift (de Oliveira and Mohriak, 2003; Matos, 2000; Mohriak et al., 2000; Chang et al., 1992; Matos, 1992; Milani and Davison, 1988; Castro, 1987). Rifting commenced in the Latest Jurassic/Berriasian and lasted until the Mid-Barrêmian, well documented through extensive hydrocarbon exploration (Matos, 2000, 1999; Szatmari and Milani, 1999; Magnavita et al., 1994; Chang et al., 1992; Milani and Davison, 1988).

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by the Late Jurassic/Early Cretaceous-aged Colorado, Macachín, Laboulaye/General
 Levalle and San Luis basins in the South, Southwest and West, respectively (Fig 7;
 Pángaro and Ramos, 2012; Franke et al., 2006; Webster et al., 2004; Urien et al.,
 1995; Zambrano and Urien, 1970). Basement trends deduced from seismic and poten-
 tial field data indicate, similar to the Salado Basin, E–W trending rift structures, orthog-
 onal to the SARS and point to to N–S directed extension/transtension (Pángaro and
 Ramos, 2012; Franke et al., 2006, J. Autin personal communication, 2012). Pángaro
 and Ramos (2012) estimate around 45 km (20 %) N–S directed extension for the Col-
 orado basin. Our model assumes 80 km of NE–SW directed transtension for the basin
 from 150 Ma to Base Aptian when relative motions between Patagonian Plates and
 South America cease (Somoza and Zaffarana, 2008).

The Colorado Basin marks the transition between the blocks related to the South
 American Platform and the Patagonian part of South America (Pángaro and Ramos,
 2012), which we here summarise as Patagonian Extensional domain. The Patagonian
 lithosphere south of the Colorado Basin is composed of a series of amalgamated mag-
 matic arcs and terranes with interspersed Mesozoic sedimentary basins (Ramos, 2008;
 Macdonald et al., 2003; Ramos, 1988; Forsythe, 1982). For the purpose of this paper,
 the North Patagonian Massif, Rawson Block, Deseado Block and Malvinas/Falkland
 Island Block are not separately discussed as deformation in the Colorado and Salado
 basins largely accounts for clockwise rotation of the Patagonian South America during
 the Late Jurassic to Aptian.

3.2.3 The Gastre shear zone

The Gastre shear zone is used in previous plate tectonic models as major intraconti-
 nental shear zone, separating Patagonian blocks from the main South American plate
 (Torsvik et al., 2009; Macdonald et al., 2003). However, no substantial transtensional or
 transpressional features along this proposed faults zone are recognised in this part of
 Patagonia, nor is the geodynamic framework of southern South America favouring the
 proposed kinematics. A detailed geological study of the Gastre Fault zone area lead

von Gosen and Loske (2004) to conclude that there is no evidence for a late Jurassic–Early Cretaceous shear zone in the Gastre area. Our model does not utilise a Gastre Shear Zone to accommodate motions between the South American and Patagonian blocks.

4 Plate reconstructions

The plate kinematic evolution of the South Atlantic rift and associated intracontinental rifts preserved in the African and South American plates, is presented as self-consistent kinematic model with a set of finite rotation poles (Table 1). In the subsequent description of key timeslices we refer to Southern Africa (SAf) fixed in present day position. We will focus on the evolution of the conjugate South Atlantic margins. For paleo-tectonic maps in 1 Myr time intervals please refer to the electronic supplements.

4.1 Kinematic scenarios

Plate motions are commonly expressed in the form of plate circuits or rotation trees in which relative rotations compound in a time-dependent, non-commutative way. The core of our plate tectonic model is the quantified intraplate deformation which allows us to indirectly model the time-dependent velocities and extension direction in the evolving SARS. Between initiation and onset of seafloor spreading, the plate circuit for the South America plate is expressed by relative motions between the African sub-plates (Fig. 8). Whereas the kinematics of rifting are reasonably well constrained through structural elements and sedimentation patterns, the timing of extension in those rifts carries significant uncertainties due to predominantly continental and lacustrine sediment infill as well as limited direct information from drilling into the deepest (oldest) parts of these rifts. While the regional evolution allows for a relatively robust dating of the onset of deformation at the Base Cretaceous, the onset of post-rift subsidence in the CARS and WARS, which have experienced subsequent phases of significant

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reactivation (Janssen et al., 1995; Genik, 1992; McHargue et al., 1992) is not as well constrained. The design of our plate circuit (Fig. 8) implies that the timing of rift and post-rift phases affect the resulting relative plate motions between South America and Southern Africa in a major way. We have thus tested five different kinematic scenarios by varying the rift start and end times of the WARS, CARS, and EqRS to evaluate the temporal sensitivity of our plate model using the following scenarios:

1. Model PM1: Rifting along SARS, CARS, WARS, and EqRS starts simultaneously around the Base Cretaceous (here: 143 Ma). Rifting in CARS and WARS ceases at 110 Ma (Lower Albian). This model is our preferred one based on kinematics which are spatio-temporally consistent with geological evidence from all rift systems.
2. Model PM2: Rifting along SARS, CARS, WARS, and EqRS starts simultaneously at Base Cretaceous (143 Ma). Extension along CARS and WARS ceases at 100 Ma (Upper Albian).
3. Model PM3: Rifting along SARS, CARS and WARS starts at Base Cretaceous (143 Ma). Rifting along EqRS starts at Top Valangian (132 Ma). Extension in CARS and WARS stops at 110 Ma (Lower Albian).
4. Model PM4: Rifting along SARS, EqRS, and CARS starts at Base Cretaceous (143 Ma). Extension in WARS commences at Base Valangian (135 Ma). Rifting in CARS and WARS ceases at 110 Ma (Lower Albian).
5. Model PM5: Rifting along SARS and EqRS starts at Base Cretaceous (143 Ma). Rifting in WARS and CARS commences at 135 Ma, stopping at 110 Ma (Lower Albian).
6. NT91: Model parameters of Nürnberg and Müller (1991) with forced breakup at 112 Ma after Torsvik et al. (2009).

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The resulting plate motion paths are plotted against observed lineaments and structures along the conjugate South Atlantic margins and the implied spatio-temporal dynamics are evaluated (Figs. 9–11). The model of Nürnberg and Müller (1991) with Torsvik et al. (2009)'s forced break-up at 112 Ma was used for comparison.

5 The extension history for the conjugate South Atlantic passive margins implied by the various models was used as a primary criterion to eliminate possible alternative scenarios. Figure 9 shows the resulting flowlines for the six different models along the northern Gabon/Rio Muni margin. Here, the kinematics of the early extension stage implied by the alternative models allow to discern between reasonable kinematic scenarios. The largest difference is between our models (PM1-PM5) and NT91, which uses 131 Ma as start age for relative motions between the South American and African plates. The shorter duration ($\Delta t = 12$ Myrs) between the onset of plate motions and key tiepoint at Chron M0 (which is the same across all models) results in higher extensional velocities and strain rates in NT91. In the Douala and Kribi-Campo Basins (conjugate to the Brazilian Pernambuco-Paraíba margin; Figs. 4 and 7), the stratigraphy indicates a slightly later onset of subsidence and rifting compared to the other margin segments of the central SARS (Gabon/Sergipe Alagoas to Campos/Kwanza). Precambrian basement rocks have been drilled, overlain by Barrêmian to Aptian in age, approximately 15 Myrs younger than the earliest known syn-rift deposits in the SARS (Brownfield and Charpentier, 2006; Turner et al., 2003). Most likely, rifting between the NE Brazilian Borborema Province Block and the Douala/Benoué Microplates only occurred much later compared to the main SARS, as most of the pre-Barrêmian extensional deformation was taken up by the Recôncavo-Tucano-Jatobá, Araripe and Potiguar rifts. The flowlines for model NT91 indicate a fast initial NNE–SSW translation of SAM relative to SAf by about 100 km for the time from 131–126 Ma implying significant transpression along the northern Gabon/Rio Muni margin, which is not evident from the geological record during this interval (e.g. Brownfield and Charpentier, 2006; Turner et al., 2003). The initial extension phase is followed by a sudden E–W kink in plate motions from

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126 Ma to 118 Ma before the flowlines turn SW–NE, parallel to our model(s) for the time of the CNPS.

Models PM4 and PM5 result in NW–SE directed compression between SAM and SAf during the initial extension phase (Fig. 9), which is not supported by observations.

This indicates that rifting in the WARS and CARS has most likely started at the same time when rifting in the SARS commenced. Flowlines produced by PM2 and PM3 deviate between 126 and 120 Ma from our preferred model, indicating more transpression during this time interval.

Along the Namibian margin (Fig. 10), model NT91 yields plate motions paths which are not reconcilable with gravity signatures along the margin for the conjugate SAf–Patagonian plates. PM2–PM5 deviate slightly from PM1 during the 126–120 Ma interval. Significant differences in the initial extension directions between SAM–SAf and the Patagonian Terranes–SAf occur in the central Orange Basin, conjugate to the Colorado and Salado Basins. Northward from here, SAM–SAf relative motions are WNW–ESE, while predicted extension directions between the Patagonian Terranes and SAf south of the central Orange Basin imply transtensional opening of the southernmost SARS in NE–SW direction. This is a result of the relative clockwise rotation of the Patagonian Terranes to SAM and in accordance with structural observations from the southern Orange Basin (H. Koopmann, personal communication, 2012) and the changing trend of the main gravity lineaments (Fig. 10).

Figure 11 shows that our plate models predict an initial NW–SE directed extension in the inner part of the Santos basin, oriented orthogonally to the main gravity gradients, Moho topography and proximal structural elements (e.g. Stanton et al., 2010; Chang, 2004; Meisling et al., 2001). In the western Santos basin we model the initial extension phase to be focussed between the São Paulo High/SAf and SAM, until the onset of the third extensional phase around the Barrêmian/Aptian boundary, a time when the inferred oceanic Abimael spreading becomes extinct (Figs. 8 and 11; Scotchman et al., 2010) and the São Paulo High is translated from the SAf to the SAM plate.

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We prefer model PM1 due to its simplicity and consistency with the geological (implied strain rates, timing of events) and geophysical observations (alignment of flow-lines with lineaments identified in the gravity data) in nearly all rift systems. Models PM2 and PM4 and result in compression between SAf and SAM for the initial periods of extension and are hence not deemed suitable as there is no evidence in the geological record of significant compressive motions between these two plates in the Gabon/Sergipe Alagoas margin during the Early Cretaceous (Fig. 9). All our models (PM1-PM6), however, show a good agreement in overall orientation and implied kinematics, confirming the robustness of our methodology of constructing indirect plate motion paths for the evolution of the SARS through accounting for intraplate deformation.

4.2 Fit reconstruction and the influence of Antarctic plate motions

The fit reconstruction (Fig. 12) is generated by restoring the pre-rift stage along the intraplate WARS and CARS for the African sub-plates, and in the Recôncavo-Tucano-Jatobá, Colorado and Salado Basins for the South American sub-plates using estimates of continental extension (see Sect. 3). We then use area balanced crustal-scale cross sections along the South Atlantic continental margins, (Sect. 2.3, Fig. 3) in combination with the restored margin geometry published by Chang et al. (1992) to construct pre-rift continental outlines. Margins along the Equatorial Atlantic are generally narrow (Azevedo, 1991) and associated with complex transform fault tectonics and few available published crustal scale seismic data, the location of the LaLOC here is only based on potential field data. We allow on average 100 km of overlap between the present-day continental margins in the EqRS (Fig. 13), compared to a few hundred km in the central part of the SARS. Total stretching estimates for profiles across the margins for the central and southern South Atlantic segment range between 2.3–3.8 for the 10 profiles shown in Fig. 3. South America is subsequently visually fitted against the West African and African Equatorial Atlantic margins using key tectonic lineaments such as fracture zone end points and margin offsets (Fig. 12). Transpressional deformation has

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affected the conjugate Demerara Rise/Guinea Plateau submerged promontories, resulting in shortening of both conjugate continental margins during the opening of the SARS (Basile et al., 2013, 2005; Benkheilil et al., 1995). Our reconstructions hence show a gap of ≈ 50 km between the Demerara Rise and the Guinea Plateau at the western EqRS as we have not restored this shortening (Fig. 12).

The dispersal of Gondwana into a western and eastern part was initiated with continental rifting and breakup along the incipient Somali-Mozambique-Wedell Sea Rift (e.g. König and Jokat, 2006; Norton and Sclater, 1979). Displacement of Antarctica as part of eastern Gondwana southwards relative to SAM and SAf creates an NE–SW extensional stress field affecting southernmost Africa and the present-day South American continental promontory comprised of the Ewing Bank and Malvinas/Falkland Island and the Proto-Weddell sea from the Mid-Jurassic onwards (König and Jokat, 2006; Macdonald et al., 2003). This is recorded by Oxfordian-aged syn-rift sediments in the Outeniqua Basin in South Africa as well as subsidence and crustal stretching in the North Falkland Basin and the Maurice Ewing Bank region (Fig. 7; Paton and Underhill, 2004; Macdonald et al., 2003; Bransden et al., 1999). The overall NE–SW extension causes a clockwise rotation of the Patagonian blocks away from SAf and SAM commencing at ≈ 150 Ma, and initiates rifting in the North Falkland, Colorado and Salado basins which precedes relative motions between the African and South American plates (Fig. 12). The resulting relative motion in the southern part of the SARS is NE–SW directed transtension (Fig. 10).

4.3 Phase I: Initial opening – Base Cretaceous to upper Hauterivian (143–126.57 Ma)

Extensional deformation along the WARS, CARS and SARS is documented to start in the Earliest Cretaceous (Berriasian) by the formation of intracontinental rift basins and deposition of lacustrine sediments along the conjugate South Atlantic margins (Poropat and Colin, 2012; Chaboureaud et al., in press; Dupré et al., 2007; Brownfield and Charpentier, 2006; Bate, 1999; Cainelli and Mohriak, 1999; Coward et al., 1999;

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Karner et al., 1997; Chang et al., 1992; Guiraud et al., 1992; Brink, 1974). In the southern part of the SARS, SW-directed extension has already commenced in the latest Jurassic with syn-rift subsidence in the Colorado, Salado, Orange and North Falkland Basins (Séranne and Anka, 2005; Jones et al., 2004; Clemson et al., 1999; Maslanyj et al., 1992; Stoakes et al., 1991). Evidence for deformation and rifting along the EqRS during the Early Cretaceous is sparse, however, indications for Magmatism and transpressional deformation are found in basins along the margin (e.g. Marajó Basin, São Luis Rift; Soares Júnior et al., 2011; Costa et al., 2002; Azevedo, 1991). The Ferrer-Urbano-Santos Arch is an E–W trending basement high between the proximal parts of the Barrerinhas basin and the onshore Parnaíba basin which was generated by transpression during the Neocomian (Azevedo, 1991).

Extension in all Major rift basins occurs at slow rates during the initial phase, with separation velocities between SAM and SAf around 2 mm a^{-1} in the Potiguar/Rio Muni segment and up to 15 mm a^{-1} in the southernmost SARS segment, closer to the stage pole equator (Fig. 14). The predominant extension direction changes from NW–SE in the northern SARS segment to WNW–ESE in the southern part, and SSW–NNE for the conjugate Patagonia-SAf segment (Figs. 14 and 12–15). Along the central SARS segment, this phase corresponds to Karner et al. (1997)'s “Rift Phase 1” with broadly distributed rifting.

Flowlines derived from the plate model for the early extension phase correlate well with patterns observed in the free air gravity field along the proximal parts of the margins, such as in the northern Orange, and inner Santos Basins (Figs. 10, 11). Along NE–SW trending margin segments, such as Rio Muni/Sergipe Alagoas and Santos/Benguela, the extension is orthogonal to the margin, whereas oblique rifting occurs in other segments. In this context we note that the strike of the Taubaté Basin in SE Brazil (“Tau” in Fig. 7) as well as observed onshore and offshore extensional structures and proximal Moho uplift in the Santos Basin (Stanton et al., 2010; Fetter, 2009; Meisling et al., 2001; Chang et al., 1992) are oriented orthogonal to our modeled initial opening direction of the South Atlantic rift. The Recôncavo-Tucano-Jatobá (RTJ) rift

opens as we model the BPB attached to the West African Congo Craton and Benoue Subplate, with SAM being relatively displaced northwestward. Here, the Pernambuco shear zone acts as continuation of the Borogop Fault Zone into NE Brazil (Matos, 1999). Potiguar Basin and Benoue Trough Make up one depositional axis while the RTJ and inner/northern Gabon belong to the central South Atlantic segment.

Around 138 Ma (Mid-Berriasian), break up and seafloor spreading starts in isolated compartments between the Rawson Block and the continental margin south of the Orange Basin, and by 132 Ma, all but the conjugate Orange Basin/Salado Block segment in the southern SARS have broken up and seafloor spreading commenced south of the Walvis Ridge/Florianopolis High (Fig. 15). The Tristan da Cuñha hotspot has been located beneath the Pelotas-Walvis segment of the SARS since 145 Ma (Figs. 12–15, and paleo-tectonic Maps in electronic supplement) and likely caused significant alteration of the lithosphere during the early phase rifting, with the eruption of the Paraná-Etendeka Continental Flood basalt province occurring between 138–129 Ma (Peate, 1997; Stewart et al., 1996; Turner et al., 1994). While we have not included a temporary plate boundary in the Paraná Basin in our model, evidence from the Punta Grossa and Paraguay dyke swarms (Peate, 1997; Oliveira, 1989) points to NE–SW directed extension, similar to the “Colorado Basin-style” lithospheric extension orthogonal to the main SARS (Turner et al., 1994).

Crustal breakup south of the Florianopolis/Walvis Ridges is modeled at 136 Ma, coinciding with the main eruption phase of the Paraná-Etendeka flood basalt province. Between 136–132 Ma, the plume center is located beneath the present-day South American coastline in the northern Pelotas Basin. Our reconstructions indicate that the westernmost position of a Tristan plume (assumed to be fixed) with a diameter of 400 km is more than 500 km east of the oldest Paraná flood basalts, at the northern and western extremities of the outcrop (Turner et al., 1994). Oceanic magnetic anomalies off the Pelotas/northern Namibe margins indicate asymmetric spreading with a predominant accretion of oceanic crust along the African side (Moulin et al., 2009; Rabinowitz and LaBrecque, 1979), which in our reconstructions can be explained through plume-ridge

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interactions of high Magma volume fluxes and relatively low spreading rates (Fig. 14; Mittelstaedt et al., 2008). The São Paulo – Rio de Janeiro coastal dyke swarms, emplaced between 133–129 Ma, have any extrusive equivalents in the Paraná LIP (Peate, 1997). The dykes are oriented orthogonal to our modeled initial extension direction, both along the Brazilian as well as along the African margin in southern Angola. Along with a predominant NE–SW striking metamorphic basement grain presenting inherited weaknesses (Almeida et al., 2000), these dykes are probably related to lithospheric extension along the conjugate southern Campos/Santos–Benguela margin segment of the SARS.

In the southern segment, the Falkland-Aghulas Fracture zone is established and the Maurice Ewing block starts moving with the Patagonian plate around 134 Ma.

Towards the upper Hauterivian (127 Ma), the width of the enigmatic Pre-salt Sag basin width has been created by slow, relative extension between SAM and SAf, with extension velocities ranging between 7–9 mm a⁻¹ (Campos/Jatobá, Fig. 14).

4.4 Phase II: Equatorial Atlantic rupture (126.57–120.6 Ma)

Following the initial rifting phase which is characterised by low strain rates, deformation along the EqRS between NWA and northern SAM intensifies due to strain localisation and lithospheric weakening (Heine and Brune, 2011). Marginal basins of the EqRS record increasing rates of subsidence/transpression (Azevedo, 1991) and in the southern South Atlantic seafloor spreading anomalies M4 and M0 indicate a 3-fold increase in relative plate velocities between SAM and African Plates (Figs. 16 and 14). Velocity increases of similar magnitude, albeit with a different timing, are reported by Torsvik et al. (2009); Nürnberg and Müller (1991). Along the EqRs, Azevedo (1991) describes a set of transpressional structures in the Barreirinhas Basin which caused folding of Albian and older strata and reports 50–120 km of dextral strike slip along the Sobradinho Fault in the proximal Barrerinhas basin, pointing towards an early dextral displacement. With the changed kinematics, SAM now rotates clockwise around NWA, causing transtensional opening of basins in the eastern part of the EqRS and about 20 km of

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transpression along the Demerara Rise and Guinea Plateau at the western end of the EqRS. This is in accordance with observed compressional structures along the southern margin of the Guinea Plateau and the northeastern margin of the Demerara Rise (Basile et al., 2013; Benkhelil et al., 1995).

5 The increase in extensional velocities jointly occurs with a sudden change in extension direction from NW–SE to more E–W (Fig. 14). Depending on the distance from the stage pole for this time interval, the directional change is between 75° in the northern SARS (Rio Muni-Gabon/Potiguar-Sergipe Alagoas segment) and 30° in the southern Pelotas/Walvis segment. The directional change visible in the flowlines agrees very well
10 with a pronounced outer gravity high along the Namibian margin (Fig. 10) and lineaments in the Santos Basin (Fig. 11). This change in the plate motions had severe effects on the patterns and distribution of extension in the SARS. Karner et al. (1997) report a 100 km westward step of the main axis of lithospheric extension in the Gabon/Cabinda margin segment during their second rift phase (Hauterivian to late Barrêmian). Along
15 the Rio Muni/ North Gabon margin a mild inversion in the pre-breakup sediment is observed (Lawrence et al., 2002) which we relate to the change in plate kinematics, manifested in this margin segment as change from orthogonal/slightly oblique extension to transform/strike slip. In the Santos Basin, the change in extensional direction results in transtensional motions, most likely responsible for the creation of the Cabo
20 Frio fault zone and localised thinning in proximal parts of the SW Santos basin, now manifested as an “Axis of Basement Low” (Modica and Brush, 2004) north of the São Paulo High. By the time of change in plate motions (126.57 Ma), the Pre-salt sag basin width had been fully generated (Fig. 16). Increasing extensional velocities cause quick, highly asymmetric localisation of lithosphere deformation in the northern and
25 central SARS segments, most likely additionally influenced by the inherited basement grain/structures. This has left large parts of the Phase I rift basin preserved along the Gabon-Kwanza margin, whereas south of the Benguela/Cabo Frio transform the Phase I rift is largely preserved on the Brazilian side.

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Davison (2007) reports that from about 124 Ma (Early Aptian using Gradstein et al., 2004), extensive evaporite sequences are deposited in areas north of the Walvis Ridge, starting with the Paripuiera salt in the northern Gabon/Jequitinhonha segment at 124 Ma and the slightly younger Loeme evaporites in the Kwanza basin. We note that in our reconstructions, seafloor spreading propagated northwards into the south-western part of the Santos Basin (the now aborted Abimael ridge; Scotchman et al., 2010; Mohriak et al., 2010; Gomes et al., 2009) towards the end of this phase. The São Paulo High remains part of the African lithosphere, which explains the “Cabo Frio counterregional fault trend” in the northern Santos Basin (Modica and Brush, 2004). Prior NW–SE extension, paired with additional thinning and transform motions along the Cabo Frio fault system (Stanton et al., 2010; Meisling et al., 2001) could have formed a shallow gateway through the inner parts of the Santos Basin, allowing the supply of seawater into the isolated central SARS. Dynamic, plume-induced topography (Rudge et al., 2008) from the extensive magmatic activity in the Paraná-Etendeka Igneous province might have caused additional lithospheric buoyancy of the extending lithosphere in the Santos basin.

Seafloor spreading is fully established in a Proto-South Atlantic ocean basin (Pelotas-Walvis segment to Falkland/Aghulas fracture zone), while oceanic circulation in this segment was probably restricted as the Falkland/Malvinas–Maurice Ewing Bank continental promontory had not cleared the Southern African margin (Fig. 17).

4.5 Phase III: Break up – Aptian to late Albian (120.6–100 Ma)

Magnetic anomaly chron M0 (120.6 Ma) is clearly identified in large parts of the southern South Atlantic and provides, along with established fracture zones, one Major tie-point for our reconstruction. Further lithospheric weakening and strain localisation along the EqRS resulted in widespread transtensional motions and related complex basin formation in the marginal basins (Basile et al., 2005; Matos, 2000, 1999; Azevedo, 1991) causing a second increase in extensional velocities between the African and SAM plates and a minor change in separation direction from 120.6 Ma onwards (Fig. 14).

We here linearly interpolate the plate velocities during the CNPS (120.6–83.5 Ma) only adjusting plate motion paths along well established fracture zones.

By 120 Ma (Lower Aptian, Fig. 17) continental breakup has occurred in the northernmost SARS between the Potiguar/Benin and Pernambuco–Paraíba/Rio Muni margin segments and between the conjugate northern Gabon/Jequitinhonha–Camamu margins with incipient breakup in the remaining part of the central SARS (Espírito Santo/Cabinda-Campos/Kwanza). South of the Cabo Frio/Benguela transform, changes in plate motions resulted in deformation to jump from the Avedis and Abimael ridges in the southwestern Santos basin (Scotchman et al., 2010; Mohriak et al., 2010; Gomes et al., 2009) towards the African side, rifting the São Paulo High away from the Namibian/Benguela margin. Extensive evaporite deposition continues in most parts of the deforming central SARS, peaking in Mid-Aptian times (Karner et al., 2007; Davison, 2007).

By 115 Ma (Middle Aptian, Fig. 18), large parts of the SARS and EqRS have broken up diachronously and entered post-rift thermal subsidence. Our model predicts breakup in the Campos/Kwanza segment by 119 Ma, in the westernmost part of the EqRS at 118 Ma, in line with deep water basin conditions reported between the Guinea and St. Paul Fracture zones (Jones, 1987). In the EqRS our model predicts accretion of oceanic lithosphere in the Deep Ghanaian Basin from 117 Ma onwards, and break up along the southern Campos/Benguela margin segment in the SARS around 115 Ma. For the Gabon margins, Dupré et al. (2007) and Karner et al. (1997) assume the onset of rifting at around 118 Ma, and Late Barrêmian–Early Aptian, respectively, which is in agreement with our model. Subsidence data from nearly all margin segments in the SARS indicate cessation of fault activity and a change to post-rift thermal subsidence by this time, with the exception of the outer Santos Basin, where the final breakup between SAf and SAm occurs between 113–112 Ma. This timing is in agreement with the deposition of the youngest evaporites in the outer Santos Basin around 113 Ma (Davison, 2007). We hypothesise that the early salt movement in the Gabon, Kwanza, Espírito Santo, Campos and Santos basins and the observed chaotic salt in

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the distal part of these basins is related to the fast localisation of lithospheric deformation, break-up and subsequent rapid subsidence during the Lower Aptian, introducing topographic gradients favouring gravitational sliding and downslope compression in the earliest postrift (Fort et al., 2004).

Relative plate motions in the CARS and WARS cease around 110 Ma in the lower Albian, with most intracontinental rift basins entering a phase of thermal subsidence before subsequent minor reactivation occurred in Post-Early Cretaceous times (Janssen et al., 1995; Genik, 1993; Maurin and Guiraud, 1993; Genik, 1992; Guiraud and Maurin, 1992; McHargue et al., 1992). The cessation of rifting in WARS and CARS results in the onset of transpression along the Côte d'Ivoire-Ghanaian Ridge in the EqRS as the trailing edges of SAM continue to move westward, while NWA now remains stationary with respect to the other African plates. The NWA transform margins now provide a backstop to the westward-directed motions of SAM, causing compression associated with up to 2 km of uplift to occur along the Ghanaian transform margin between the Middle to Late Albian (Antobreh et al., 2009; Basile et al., 2005; Pletsch et al., 2001; Clift et al., 1997). Complete separation between African and South American continental lithospheres is achieved at 104 Ma (Fig. 20), while the oceanic spreading ridge clears the Côte d'Ivoire/Ghana Ridge by 100–99 Ma.

5 Conclusions

We have presented a new plate kinematic model for the evolution of the South Atlantic rifts. Our model integrates intraplate deformation from temporary plate boundary zones along the West African and Central African Rift Systems as well as from Late Jurassic/Early Cretaceous rift basins in South America to achieve a tight fit reconstruction between the major plates. By constructing a rotation tree that describes the motions of South America to Southern Africa through relative plate motions between African sub-plates, we are able to model the time-dependent pre-breakup extension history of the South Atlantic rift system. Three main phases with distinct velocity and kinematics

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result through the extension along the Central African, West African and Equatorial Atlantic rift systems which have severe effects on the dynamics of continental lithospheric extension in the evolving South Atlantic rift from the Early Cretaceous to final separation of Africa and South America in the Upper Albian (104 Ma).

5 An initial phase of slow E–W extension in the South Atlantic rift basin from 143 Ma (Base Cretaceous) to 127 Ma (Upper Hauterivian) caused distributed extension in W–E direction. The second phase from 126–121 Ma (Upper Hauterivian to Base Aptian) is characterised by rapid lithospheric weakening along the Equatorial Atlantic rift resulting in increased extensional velocities and a change in extension direction to SW–NE. The last phase, culminating in diachronous breakup along the South Atlantic rift and formation of the South Atlantic ocean basin, commences at 120 Ma and is characterised by a further increase in plate velocities with a minor change in extension direction.

10 We argue that our proposed three-stage kinematic history can account for most basin forming events in the Early Cretaceous South Atlantic, Equatorial Atlantic, Central African and West African Rift Systems and provide a robust quantitative tectonic framework for the formation of the conjugate South Atlantic margins. In particular, our model addresses the following issues related to the South Atlantic basin formation:

- We achieve a tight fit reconstruction based on structural restoration of the conjugate South Atlantic margins and intraplate rifts, without the need for complex intracontinental shear zones.
- The orientation of the Colorado and Salado Basins, oriented perpendicular to the main South Atlantic rift are explained through clockwise rotation of the Patagonian sub-plates. This also implies that the southernmost South Atlantic rift opened obliquely in a NE–SW direction.
- The formation of the enigmatic Pre-salt sag basin along the West African margin is explained through a multi-phase and multi-directional extension history in which the initial sag basin width was created through slow ($7\text{--}9\text{ mm a}^{-1}$) continental lithospheric extension until 126 Ma (Late Hauterivian).

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- Continental break-up in the southern segment of the South Atlantic rift occurred at around 135 Ma, pre-dating the Paraná-Etendeka volcanism.
- Strain weakening along the Equatorial Atlantic Rift caused an at least 3-fold increase of plate velocities between South America and Africa between 126–121 Ma, resulting in rapid localisation of extension along the central South Atlantic rift.
- Linear interpolation of plate motions between 120.6 Ma and 83.5 Ma yield break-up ages for the conjugate Brazilian and West African margins which are corroborated by the onset of post-rift subsidence in those basins.

We conclude that our multi-direction, multi-velocity extension history can explain the key events related to continental breakup in the South Atlantic rift realm, including the enigmatic Pre-salt sag basin and that robust plate tectonic frameworks for the pre-breakup evolution of passive margins can shed new light on our understanding of the dynamics of lithosphere deformation during rifting.

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Plate reconstructions were made using the open-source software GPlates (<http://www.gplates.org>), all figures were generated using GMT (<http://gmt.soest.hawaii.edu>; Wessel and Smith, 1998). Structural restorations were partly done using Midland Valley's Move software with an academic software license to The University of Sydney.

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Supplementary material related to this article is available online at:
<http://www.solid-earth-discuss.net/5/41/2013/sed-5-41-2013-supplement./pdf>.

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Table 1. Finite rotations parameters for main rigid plates for preferred South Atlantic rift model M1. Abbreviations are Abs – absolute reference frame, SAf – Southern Africa, NEA – Northeast Africa, NWA – Northwest Africa, Sal – Salado Subplate, NPM – North Patagonian Massif block, CM – Mesozoic magnetic anomaly chron, y – young, o – old. magnetic anomaly timescale after Gee and Kent (2007).

Moving plate	Age	Rotation pole			Fixed plate	Comment
		Lon	Lat	Angle		
SAf	100.00	14.40	-29.63	-20.08	Abs	O'Neill et al. (2005)
SAf	110.00	6.61	-29.50	-26.77	Abs	Steinberger and Torsvik (2008)
SAf	120.00	6.11	-25.08	-30.45	Abs	Steinberger and Torsvik (2008)
SAf	130.00	5.89	-25.36	-33.75	Abs	Steinberger and Torsvik (2008)
SAf	140.00	7.58	-25.91	-38.53	Abs	Steinberger and Torsvik (2008)
SAf	150.00	10.31	-27.71	-37.25	Abs	Steinberger and Torsvik (2008)
NEA	110.0	0.0	0.0	0.0	SAf	
NEA	143.0	4.0	34.0	1.61	SAf	Fit – This paper – Extension based on McHargue et al. (1992)
NWA	110.0	0.0	0.0	0.0	NEA	
NWA	143.0	25.21	5.47	2.87	NEA	Fit – This paper – Extension based on Genik (1993)
SAm	83.5	61.88	-34.26	33.51	SAf	Nürnberg and Müller (1991), CAN34
SAm	96.0	57.46	-34.02	39.79	SAf	Linear interpolation
SAm	120.6	51.24	-33.49	52.45	SAf	Anomaly CM0y
SAm	120.6	52.09	-34.77	51.65	NWA	Crossover M0
SAm	126.57	50.61	-34.49	53.22	NWA	Anomaly CM4 old
SAm	143.0	50.44	-34.38	53.40	NWA	Fit
NPM	124.05	0.0	0.0	0.0	Sal	
NPM	150.00	-35.27	-69.10	2.66	Sal	Fit – this paper – Extension based on Pángaro and Ramos (2012)
Sal	124.05	0.0	0.0	0.0	SAm	
Sal	150.00	-33.02	-60.52	4.40	SAm	Fit – this paper – Extension based on Stoakes et al. (1991)

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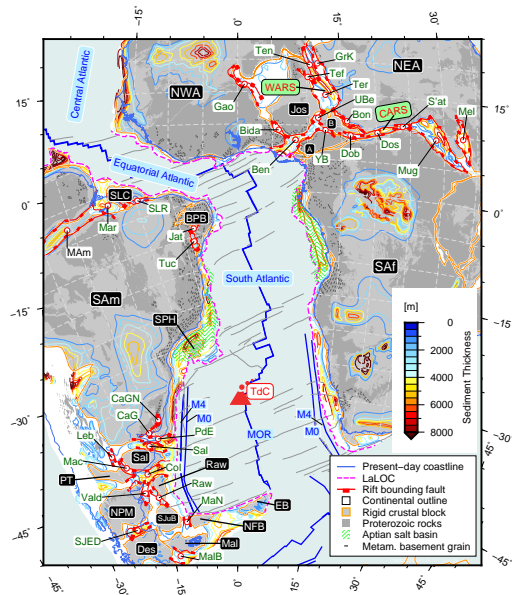


Fig. 1. Rigid crustal blocks, Jurassic-Cretaceous rift basins, and sediment isopachs, reconstructed to 83.5 Ma position (magnetic anomaly chron C34y) with Africa held fixed in present coordinates using the rotation poles of Nürnberg and Müller (1991). Proterozoic rocks are based on United States Geological Survey (2012), metamorphic basement grain as thin white lines (Exxon Production Research Company, 1985). Oceanic fractures zones are shown as gray lines. Tristan da Cuñha hotspot (TdC) indicated by volcano symbol. MOR: South Atlantic mid-oceanic ridge. Rigid crustal blocks (black boxes): SAf – Southern Africa; SAM – South America; NWA – Northwest Africa; NEA – Northeast Africa; A – Adamaoua Block, B – Bongor Block, BPB – Borborema Province Block, SLC – São Luis Craton, SPH – Sao Paulo High, NPM – North Patagonian Massif, PAM – Pampean Terrane, RAW – Rawson Block, Des – Deseado Massif in Patagonia, SJuB – San Julian Block, MAL – Malvinas Block, NFB – North Falklands Block, EWB – Maurice Ewing Bank. African rift basins (N–S): Ten – Ténéré, GrK – Grein-Kafra, Tef – Tefidet, Ter – Termit, UBe – Upper Benoue, Gao – Gao Trough, Bida – Bida Basin, Bon – Bongor Trough, Dob – Doba, Dos – Doseo, Mug – Muglad, Mel – Melut, Yola – Yola rift branch, Ben – Benoue Trough. South American rifts (N to S): SLR – Sao Luis Rift, Mar – Maranau, Jat – Jatobá, Tuc – Tucano, CaG/CaGN – Canelones Graben/-North, PdE – Punta del Este, Sal – Salado, Leb – Leboulaye, Mac – Maccachin, Col – Colorado, Vald – Valdes, Raw – Rawson, SJED – San Jorge Extensional Domain, Mal – Malvinas Basin, MaN – Malvinas Norte/North Falklands. Sediment isopachs from Exxon Production Research Company (1985) are shown as thin gray lines. Younger deformation and plates related rifting of East Africa Rift system are not shown. Lambert Azimuthal Equal Area projection.

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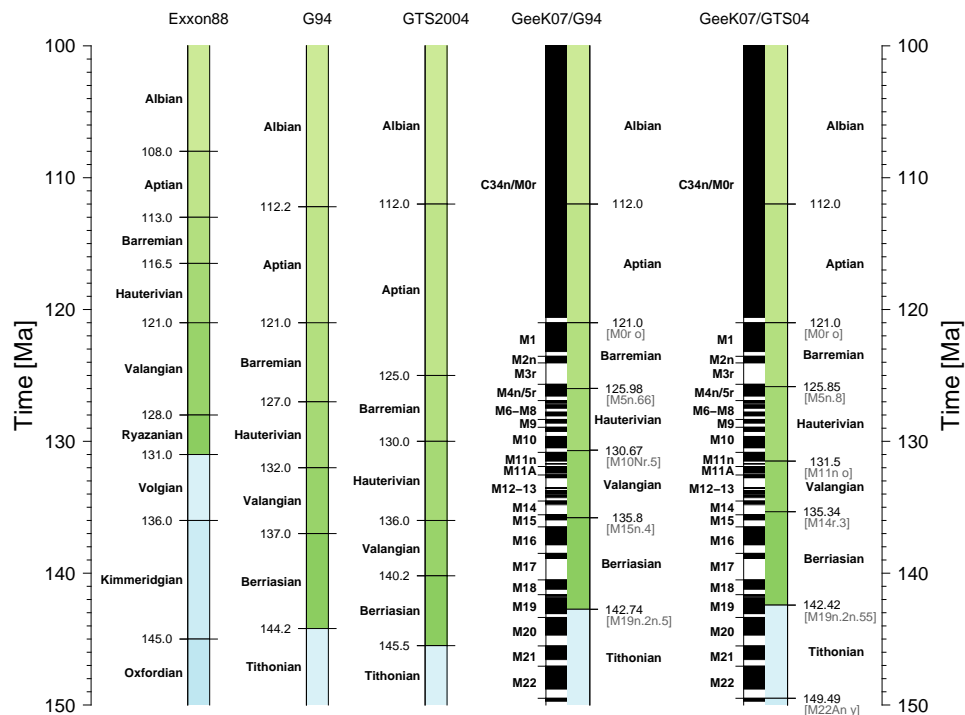


Fig. 2. Comparison of the timescales used in publications related to the South Atlantic Marginal basins and African intraplate basins and constructed hybrid timescales. GeeK07 is Gee and Kent (2007), Exxon88 is Haq et al. (1987), G94 is Gradstein et al. (1994) and GTS2004 is Gradstein et al. (2004). GeeK07/GTS04 and GeeK07/G94 show magnetic polarity time scale with stratigraphic intervals from GTS04 and G94, respectively, adjusted to tiepoints annotated on the right hand side of the stratigraphic columns (gray font), where *.N indicates the relative position from the base of the chron (e.g. M5n.66 = Base Barrémian at 125.98 Ma in GeeK07/G94).

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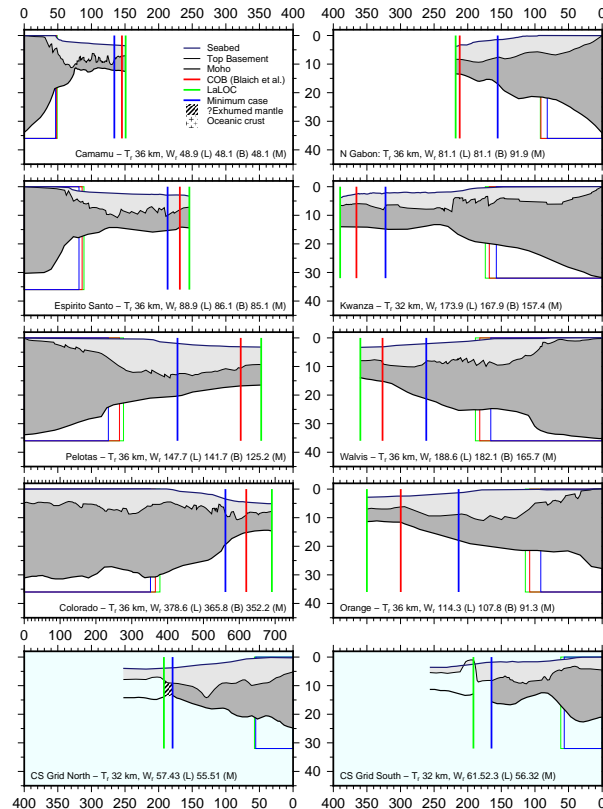


Fig. 3. Margin cross sections and area balancing based on Blaich et al. (2009, 2011) and our synthesised data based on depth-migrated and gridded CongoSPAN data along various segments of the conjugate South Atlantic Margins. T_r : restored thickness. Extend of continental crust used for area balancing: L – LaLOC (maximum estimate, landward limit oceanic crust), M – Minimum estimate (conservative), B – COB based on Blaich et al. (2009, 2011). Note that our interpretation of the CongoSPAN data (CS Grid North and South sections) includes a zone where no Moho could be identified on seismic data, which is here tentatively interpreted as exhumed mantle. Also note the difference in length of the Colorado Basin section.

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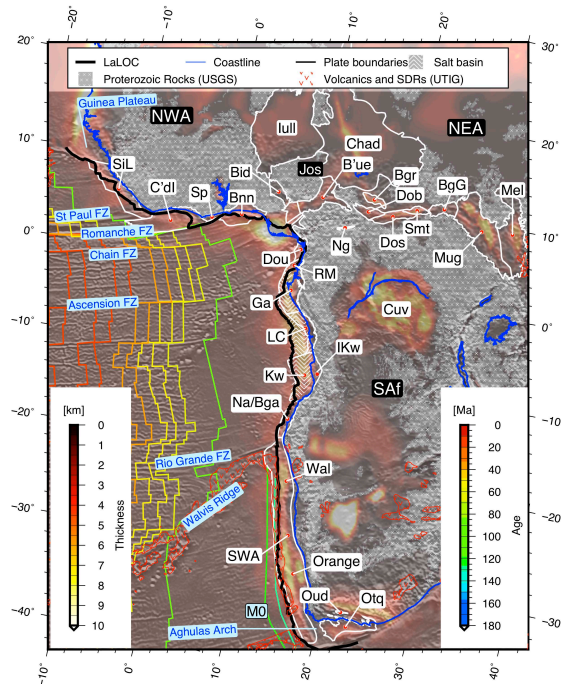


Fig. 4. Oblique Mercator Map of present day Africa, with onshore topography (ETOPO1; Amante and Eakins, 2009), offshore free air gravity (Sandwell and Smith, 2009), and gridded sediment thickness (Exxon Production Research Company, 1985) superimposed. Map legend: LaLOC – landward limit of oceanic crust, Proterozoic rocks and Mesozoic extrusive rocks based on United States Geological Survey (2012). Seaward-dipping reflectors (SDRs) based on UTIG PLATES open data (<https://www.ig.utexas.edu/research/projects/plates/data.htm>). White polygons indicate sedimentary basins (N to S): SiL – Sierra Leone Marginal, C’dI – Côte d’Ivoire marginal, Sp – Saltpond, Bnn – Benin, Bid – Bida, Iull – Iullemmeden, Chad – Chad Basin, B’ue – Benoue Trough, Bgr – Bongor Trough, Dob – Douba, Dos – Doseo, BgG – Banggara Graben, Mel – Melut, Mug – Muglad, Smt – Salamat, Ng – Ngaoundere, Dou – Douala, RM – Rio Muni, Ga – Gabon Coastal, Cuv – Cuvette Central, LC – Lower Congo, Kw – Kwanza/Cuanza, IKw – Inner Kwanza, Na/Bga – Namibe/Benguela, Wal – Walvis, SWA – South West African Marginal, Orange – Orange, Oud – Oudtshoorn, Otq – Outeniqua. Fz: Oceanic fracture zone. Colored lines are oceanic isochrons from (Müller et al., 2008), M0 – M0 Magnetic anomaly (120.6 Ma). Plate and sub-plates: NWA – Northwest Africa, NUB – Nubia/Northeast Africa, JOS – Jos Plateau Subplate and SAF – Austral Africa.

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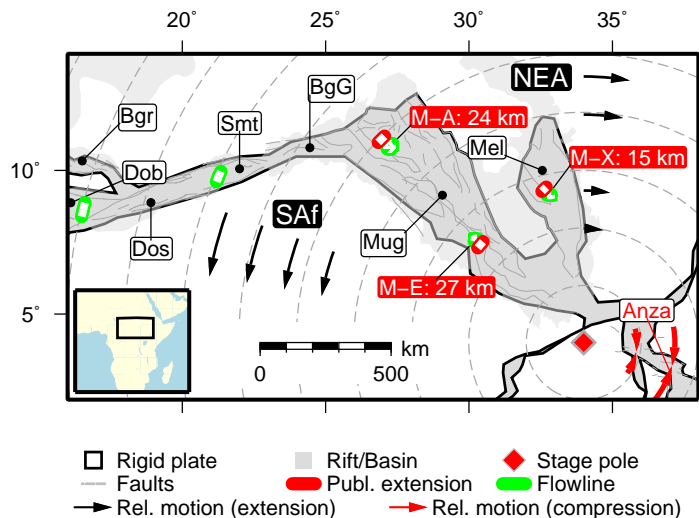


Fig. 5. Stage pole rotation and associated small circles (dashed grey lines) at 2° spacing for 145–110 Ma interval for the Central African Rift System (CARS) and associated relative plate motions at 110 Ma. Red boxes and text indicate published profiles for Melut and Muglad Basins and estimated extension values based on McHargue et al. (1992): M-A – Profile A-A', M-E – Profile E-E', M-X – Profile X-X'. Vectors shown on map only show relative motions, white core of published profiles and of green flowlines indicates actual amount of extension in km. These are ≈ 24 km for profile M-A, ≈ 27 km for profile M-E and ≈ 15 km for Profile M-X during the initial basin formation phase F1 (McHargue et al., 1992), with modeled extension of ≈ 30 km, ≈ 17 km, and ≈ 17 km (green), respectively. Red vectors indicating compression around northwestern Anza basin in Kenya (Anza) are based on mapped compressional structures (Reeves et al., 1987). Main rigid plates: SAf – Southern Africa, NEA – Northeastern Africa. Main basins and rifts: Bgr – Bongor Basin, Dob – Doba, Dos – Doseo, Smt – Salamat, BgG – Bangara Graben, Mug – Muglad, Mel – Melut, Anza – Anza Rift.

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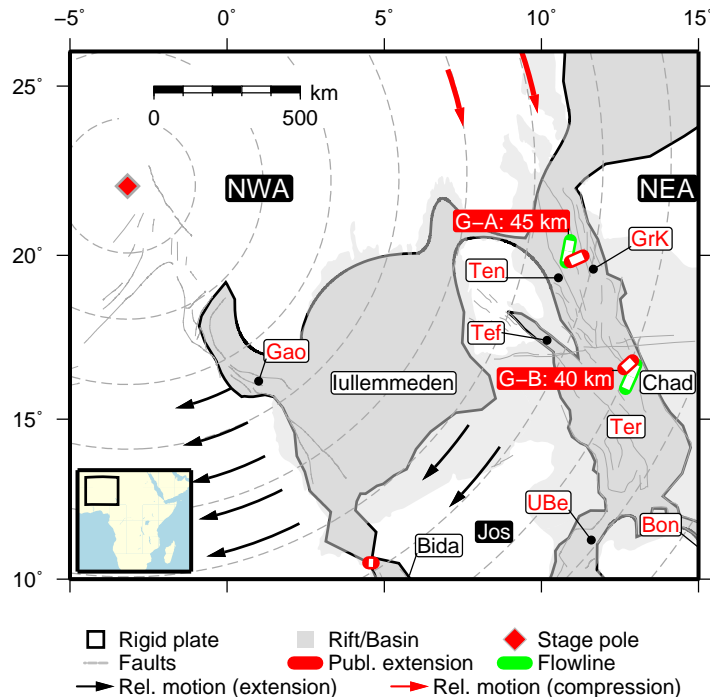


Fig. 6. Stage pole rotation and associated small circles (dashed grey lines) at 2° spacing for 145–110 Ma interval for the West African Rift System (WARS) and associated relative plate motions at 110 Ma. Red boxes and text indicate published profiles for Grein-Kafra and Termit Rifts and estimated extension values based on Genik (1992): G-A – Profile A-A', G-B – Profile B-B'. Vectors shown on map only show relative motions, white core of published profiles and of green flowlines indicates actual amount of extension in km. These are ≈ 45 km for profile G-A and 40–80 km for Profile G-B, (Genik, 1992, red;), with modeled extension of ≈ 28 km and ≈ 43 km (green), respectively. Red compressional vectors around northeast of the Grein-Kafra rift indicate possible early Cretaceous Basin-and-Swell topography related to strike-slip reactivation of basement structures in southern Lybia based on Guiraud et al. (2005). Main plates: NEA – Northeast Africa, NWA – Northwest Africa, Jos – Jos subplate. Main rifts: Gao – Gao Trough, UBe – Upper Benoue, Ter – Termit, Bgr – Bongor, Tef – Tefidet, Ten – Ténéré, GrK – Grein-Kafra. Basins: Chad - Chad Basin, lullemedden - lullemedden Basin, Bida – Bida Basin.

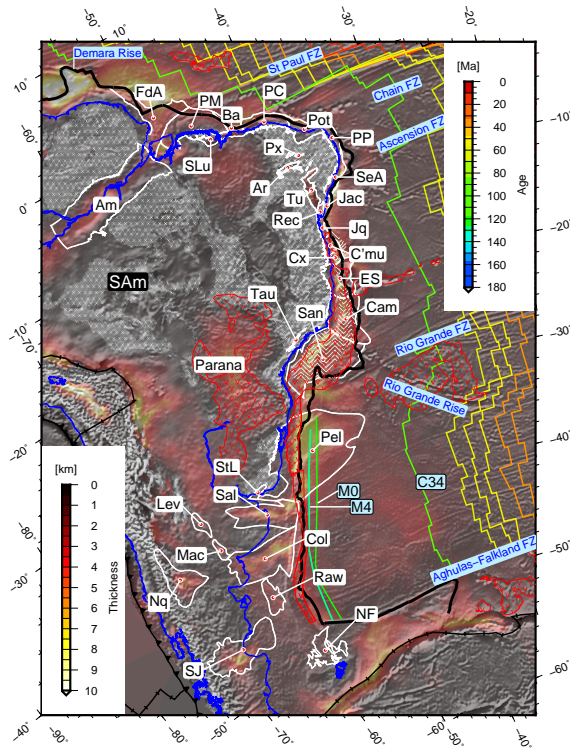


Fig. 7. Oblique Mercator map of present day South America (SAM), with onshore topography (ETOPO1; Amante and Eakins, 2009), offshore free air gravity (Sandwell and Smith, 2009), both grayscale, and gridded sediment thickness (Exxon Production Research Company, 1985) superimposed. Map legend as in Fig. 4. White polygons denote sedimentary basins (N to S): FdA – Foz do Amazon, PM – Para-Maranhao, Ba – Barreirinhas, PC – Piaui-Ceara, SLu – Sao Luis Graben, Px – Rio do Peixe, Pot – Potiguar, PP – Pernambuco–Paraiba, Ar – Araripe, SeA – Sergipe-Alagoas, Tu – Tucano, Re – Recôncavo, Jac – Jacuibe, Am – Amazonas, C'mu – Camamu, Cx – Cumuruxatiba, ES – Espirito Santo, Cam – Campos, San – Santos, Tau – Taubaté, Parana – Parana Basin, Pel – Pelotas, StL – Santa Lucia, Sal – Salado, Lev – General Levalle, Col – Colorado, Mac – Maccachin, Nq – Neuquén, Raw – Rawson, NF – North Falklands, SJ – San Jorge. Colored lines are oceanic crust ages from (Müller et al., 2008). Plate boundaries (thin back decorated lines) after Bird (2003)

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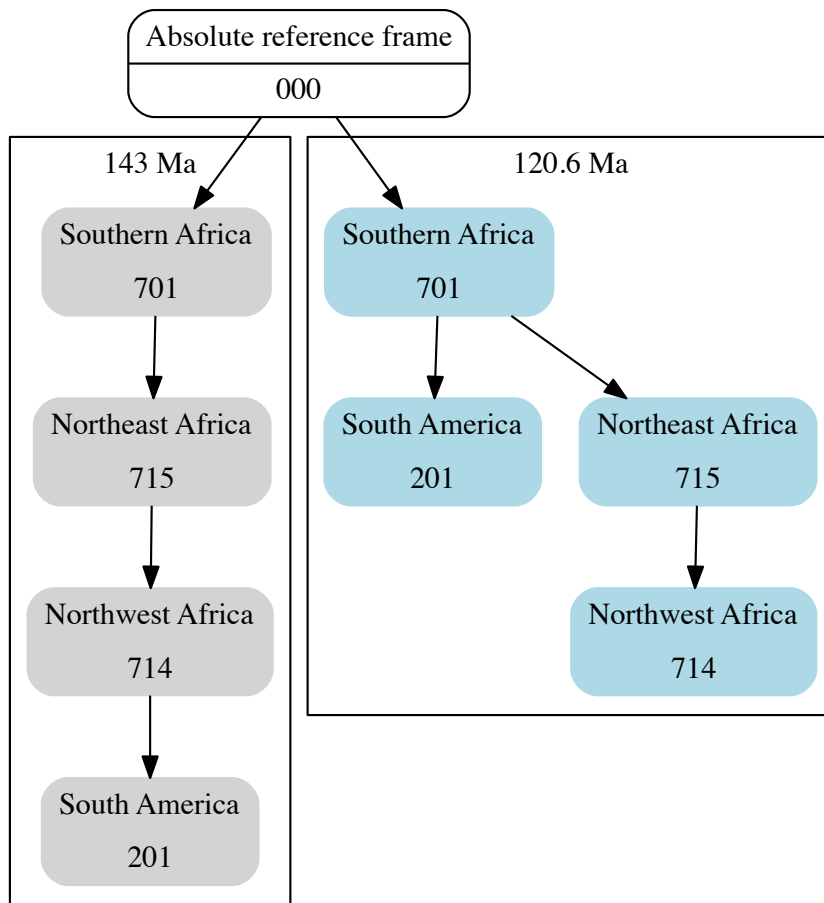


Fig. 8. Plate circuits used for the plate model at 143 Ma and from 120.6 Ma for the main lithospheric plates. Integers indicate the Plate-ID number.

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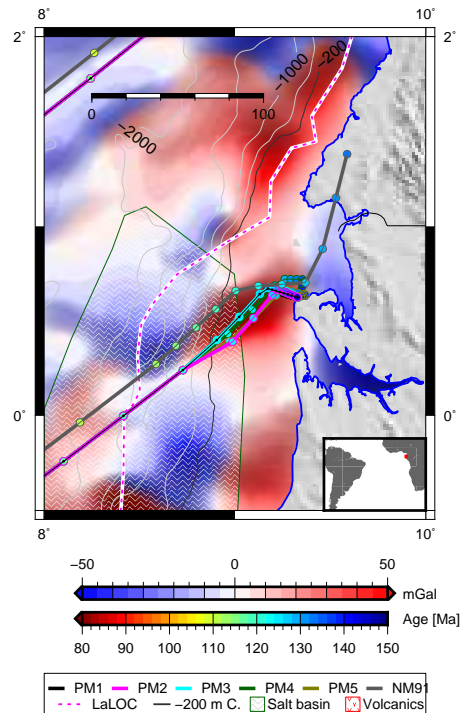


Fig. 9. Age-coded flowlines plotted on filtered free air gravity basemap (offshore) for the North Gabon/Rio Muni segment of the African margin. Initial phase flowline direction of our preferred model (PM1, thin black line with circles) is perpendicular to the trend of the present-day coastline, striking NW–SE and only turns parallel to oceanic transform zones (trending SW–NE) after ≈ 126 Ma. Note that models PM4 & PM5 induce a significant amount of compression for the initial phase of relative plate motions and do not agree with geological observations from the area. Relative motions between SAf and SAM in Model NT91 commence at 131 Ma, Circles are plotted in 2 Myr time intervals starting at 144 Ma and from 132 for NT91 (Nürnberg and Müller, 1991; Torsvik et al., 2009). Legend abbreviations: LaLOC – Landward limit of oceanic crust, C. – Contour. Free air gravity anomalies (Sandwell and Smith, 2009) filtered with 5th order Butterworth lowpass filter with 35 km wavelength.

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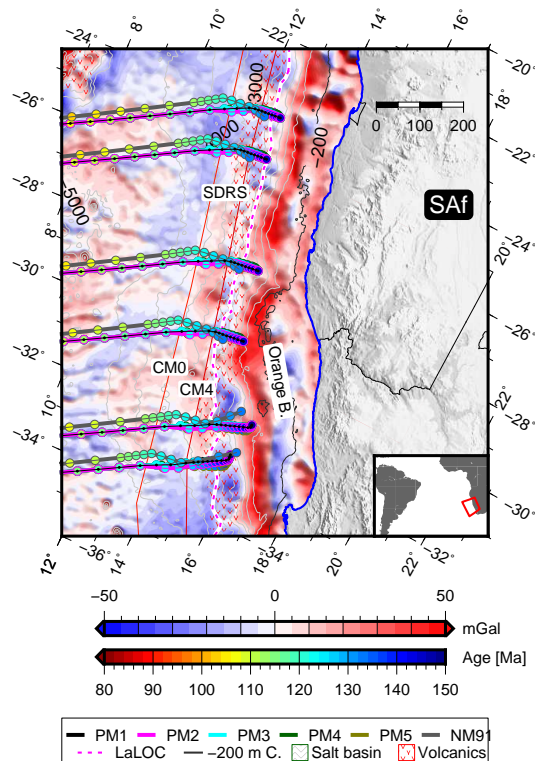


Fig. 10. Age-coded flowlines plotted on filtered free air gravity basemap (offshore) for the Orange Basin segment along the West African Margin. Early phase opening is oblique to present day Margin, with oblique initial extension of SAM relative to SAf (4 northern flowlines) in WNW–ESE direction and initial extension between Patagonian South American blocks and SAf in SW–NE direction (southern 2 flowlines). Note that the Orange Basin is located between the two divergent flowline populations and that a positive gravity anomaly is contemporaneous with the inflection point at 126.57 Ma (M4) and associated velocity increase and extension direction change (cf. Fig. 14) along the Margin. Legend/symbology and filter as in Fig. 9.

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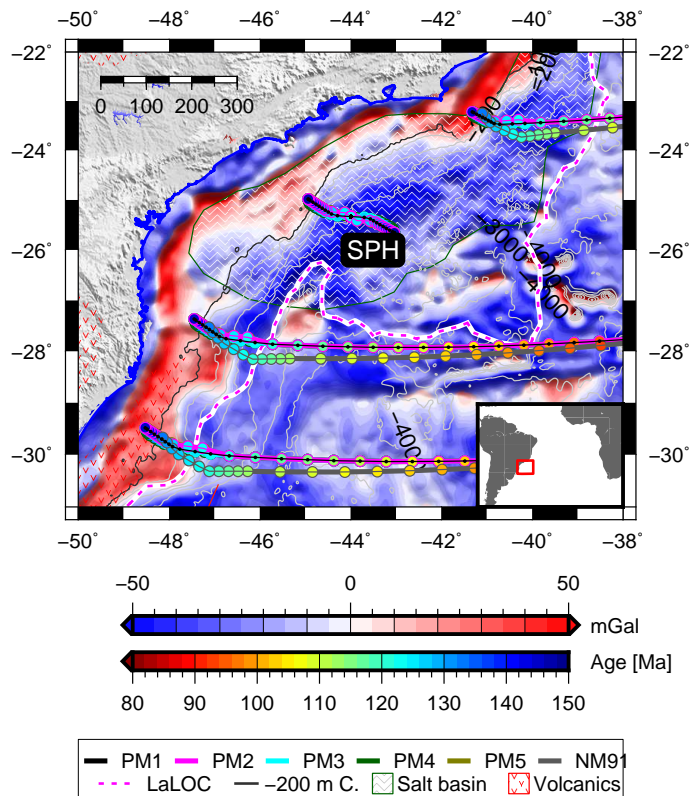


Fig. 11. Age-coded flowlines plotted on filtered free air gravity basemap (offshore) for the Santos Basin segment on South American margin. SPH- São Paulo High in the outer Santos basin. Note that initial NW–SE relative extensional direction as predicted by the plate model is perpendicular to the Santos margin hingeline (cf. Meisling et al., 2001; Stanton et al., 2010, for details on the crustal structure in along the inner Santos basin margin) and does conform to observed structural patterns in the extended continental crust of the SPH (cf. Chang, 2004). Legend/symbology and filter as in Fig. 9

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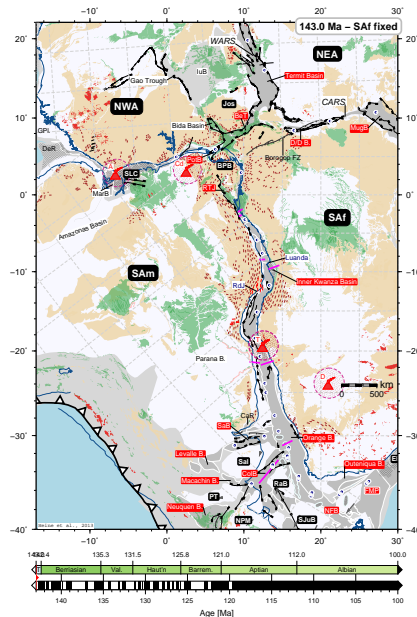


Fig. 12. Plate tectonic reconstruction at 143 Ma, Africa fixed in present-day coordinates. For Map legend see Fig. 21, bottom color scales indicate geological stages and magnetic reversals with red diamond indicating time of reconstruction, abbreviations here: T – Tithonian, Val. – Valanginian, Haut'n – Hauterivian, Barrem. – Barrémian. Rigid lithospheric blocks denoted by black labels: SAf – Austral African Plate, BoP – NE Brazilian Borborema Province plate, Jos – Jos Plateau Subplate, NEA – NE African Plate, NPM – North Patagonian Massif, PT – Pampean Terrane, RaB – Rawson Block, SaI – Salado Subplate, SAm – Main South American Plate, SJuB – San Julian Block, SLC – São Luis Craton Block. Actively extending basins are indicated by red background in label, postrift basins are indicated by light gray background in label, abbreviations: BeT – Benoue Trough, CaR – Canelones Rift, D/D B. – Doba and Doseo Basins, CoLB – Colorado Basin, luB – Lullemeden Basin, MarB – Marajó Basin, MugB – Muglad Basin, NFB – North Falkland Basin, PotB – Potiguar Basin, TRJ – Reconavo, Jatoba, Tucano Basins, SaB – Salado Basin. Other abbreviations: RdJ – Rio de Janeiro, B. – Basin, GPI. – Guyana Plateau, DeR – Demerara Rise. Present-day hotspots are shown as volcano symbol and plotted with 400 km diameter (dashed magenta colored circle with hachured fill), assuming that they are stationary over time: A – Ascension, b – Bouvet, Ch – Chad/Tibesti, Ca – Mount Cameroon, D – Discovery, T – Tristan da Cuña.

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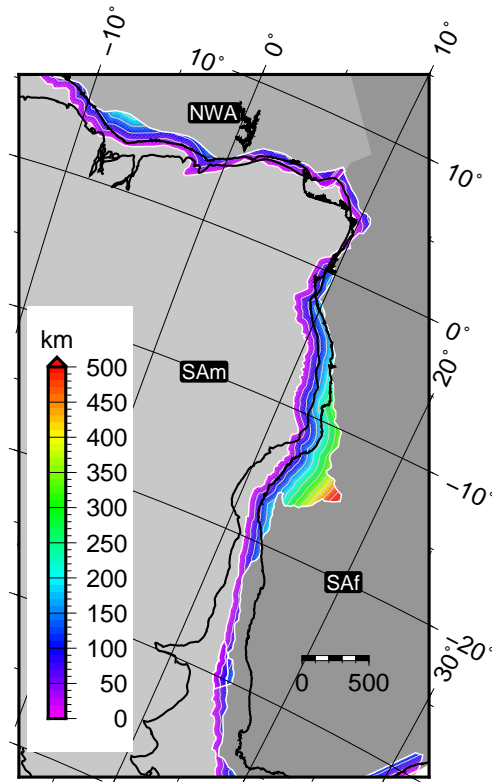


Fig. 13. Overlap between the conjugate present-day landward limits of the oceanic crust (LaLOC) for the South America (SAm), Southern Africa (SAf) and Northwest Africa (NWA). Shown is the fit reconstruction at 143 with SAF fixed in present-day position. Spacing between contour lines is 50 km, present-day coastlines as thick black lines. Note that the position of the LaLOC along the volcanic margins in southern part of the South Atlantic rift is not well constrained. Largest overlap is created between the Campos/Santos basin Margin and the southern Kwanza/Benguela Margin implying up to 500 km extension for the SE'most Santos Basin.

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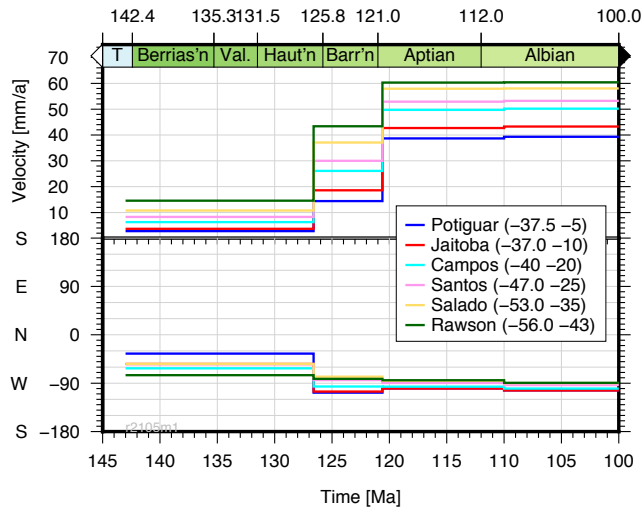


Fig. 14. Relative separation velocities and directions between 6 South American and Patagonian points relative to a fixed Southern African plate using preferred plate kinematic model. Upper portion of figure shows extensional velocities over time, lower portion shows extension direction relative to a fixed Southern African plate.

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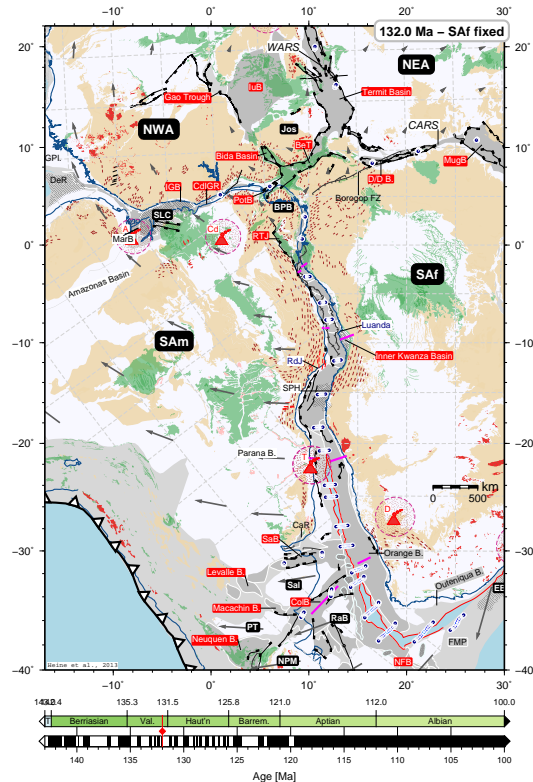


Fig. 15. Plate tectonic reconstruction at 132 Ma, with Africa fixed in present-day coordinates. For Map legend see Fig. 21, abbreviations as in Fig. 12. Note initial extension directions along the Margin rotate from NW–SE in Gabon/Sergipe-Alagoas segment to W–E in Pelotas/Walvis Basin segment with increasing distance from stage pole location. Flowlines between Patagonian blocks in southern South America and southern Austral Africa indicate and initial SW–NE directed motions between these plates (cf. Fig. 10). In West Africa, the lullemeden and Bida Basin as well as the Gao Trough are undergoing active extension. Tectonism along the Equatorial Atlantic rift increases. Additional abbreviations: DGB – Deep Ghanian Basin, CdIGR – Côte d’Ivoire/Ghana Ridge and associated Marginal basins.

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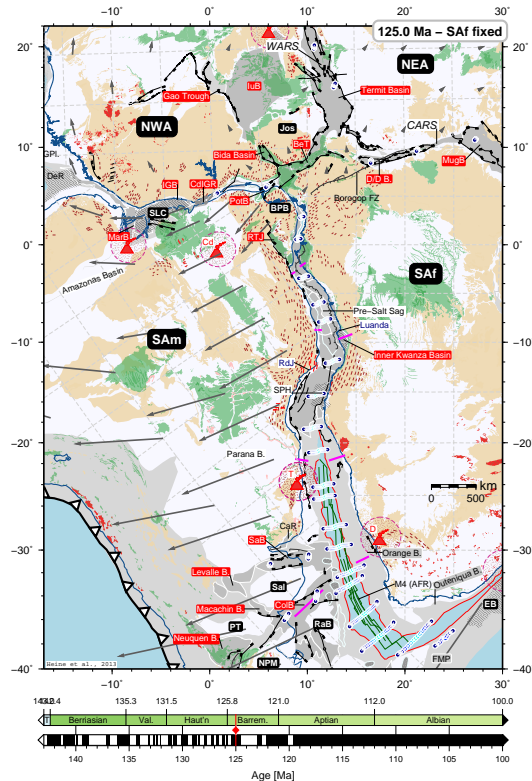


Fig. 16. [Reconstruction at 125 Ma] Plate tectonic reconstruction at 125 Ma, with Africa fixed in present-day coordinates. For Map legend see Fig. 21, abbreviations as in Fig. 12. Note that at this time, the West African Pre-salt basin width is generated and seafloor spreading is abutting against the Walvis ridge/Florianopolis ridge at the southern Margin of the Santos Basin, with extension and possible rifting along the Abimael ridge in the inner SW part of the Santos basin (cf. Scotchman et al., 2010). Relative rotation of SAM to NWA results in ≈ 20 km of transpression between the Guinea Plateau and the Demerara Rise. Rift basins along the Equatorial Atlantic rift are all actively subsiding. Additional abbreviations: SPH – São Paulo High, EB – Maurice Ewing Bank.

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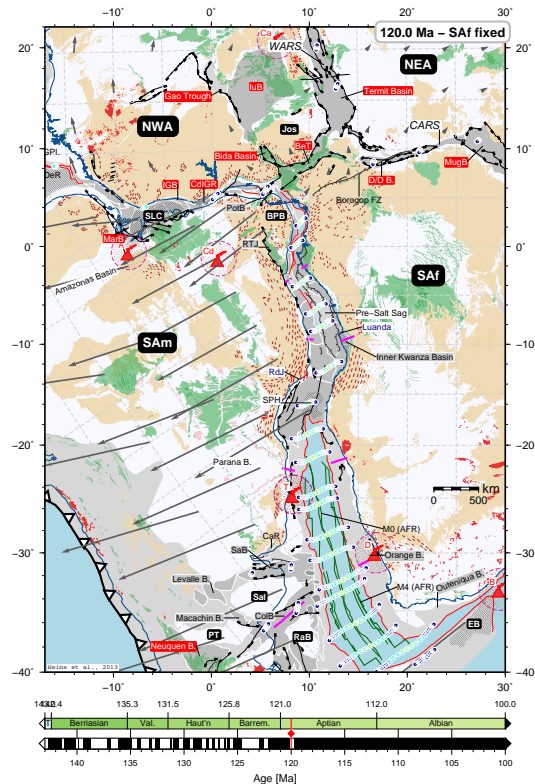


Fig. 17. Plate tectonic reconstruction at 120 Ma, with Africa fixed in present-day coordinates. For Map legend see Fig. 21, abbreviations as in Fig. 12. Significant increase in extensional velocities causes break up and subsequent seafloor spreading in the northernmost part of the South Atlantic rift extending down to the conjugate Cabinda/Espirito Santo segment. Due to changed kinematics, rifting and extension in the Santos/Benguela segment focusses on the African side, causing the transfer of the Sao Paulo High block onto the South American Plate. Breakup also occurs between Guinea Plateau and Demerara rise in the westernmost part of the Equatorial Atlantic.

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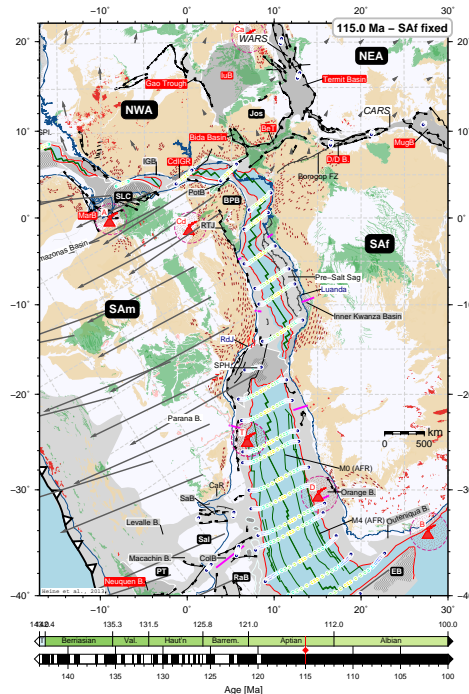


Fig. 18. Plate tectonic reconstruction at 115 Ma, with Africa fixed in present-day coordinates. For Map legend see Fig. 21, abbreviations as in Fig. 12. Continental break-up has occurred along most parts of the conjugate South American/Southern African and NW African margins apart from the “Amazon” and Côte d’Ivoire/Ghana transform segment of the Equatorial Atlantic. Oceanic accretion has already commenced in the Deep Ghanaian Basin. In the SARS, only the Benguela-Walvis/Santos segment have not yet broken up. In this segment, extension is focussed asymmetrically close to the African Margin, east of the São Paulo High. Basins in southern South America have entered the post rift phase and no significant relative motions between the rigid lithospheric blocks occur in post-Barrémian times. Post-rift thermal subsidence and possible gravitationally-induced flow of evaporite deposits towards the basin axis occurs in conjugate Margin segments of the central SARS.

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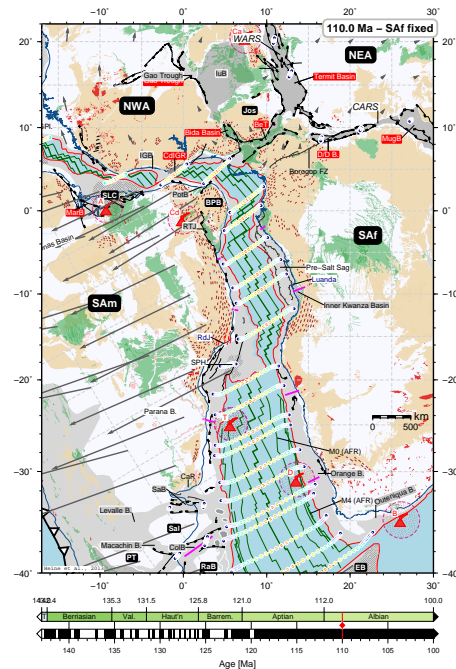


Fig. 19. Plate tectonic reconstruction at 110 Ma, with Africa fixed in present-day coordinates. For Map legend see Fig. 21, abbreviations as in Fig. 12. Full continental separation is achieved at this time, with narrow oceanic gateways now opening between the Côte d'Ivoire/Ghana Ridge and the Piaui-Ceara Margin in the proto-Equatorial Atlantic and between the Ewing Bank and Aghulas Arch in the southernmost South Atlantic. Deformation related to the break up between Africa and South America in the African intracontinental rifts ceases in post-Aptian times. Towards the Top Aptian, break up between South America and Africa has largely been finalised. The only remaining connections are between Major offset transfer faults in the Equatorial Atlantic rift and between the outermost Santos Basin and the Benguela Margin where a successively deepening oceanic gateway between the northern and southern Proto-South Atlantic is proposed. Seafloor spreading is predicted for the conjugate passive Margin segments such as the Deep Ghanaian Basin (DGB). The stage pole rotation between SAM and NWA predicts compression along the CdIGR in accordance with observed uplift during this time (e.g. Pletsch et al., 2001; Clift et al., 1997). Abbreviations: CdIGR – Côte d'Ivoire-Ghana Ridge, EB – Maurice Ewing Bank.

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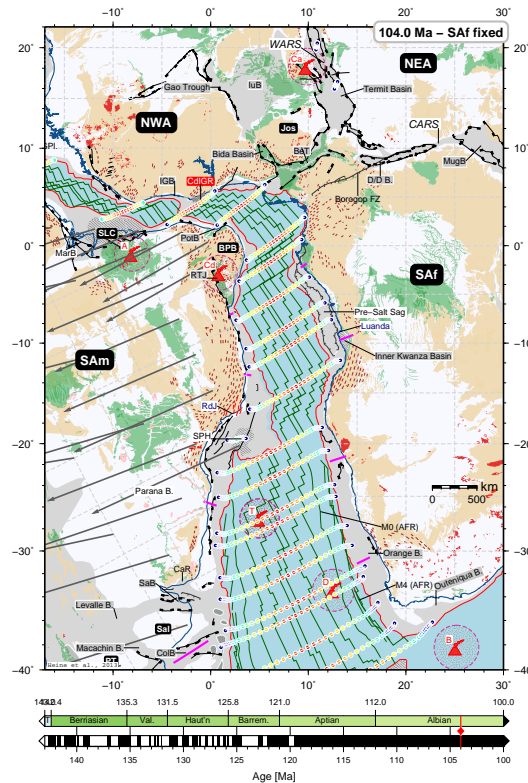


Fig. 20. Plate tectonic reconstruction at 104 Ma, with Africa fixed in present-day coordinates. For Map legend see Fig. 21, abbreviations as in Fig. 12. Full continental separation is achieved at this time, with narrow oceanic gateways now opening between the Côte d'Ivoire/Ghana Ridge and the Piauí-Ceará margin in the proto-Equatorial Atlantic and between the Ewing Bank and Aghulas Arch in the southernmost South Atlantic. Deformation related to the break up between Africa and South America in the African intracontinental rifts ceases in post-Aptian times.

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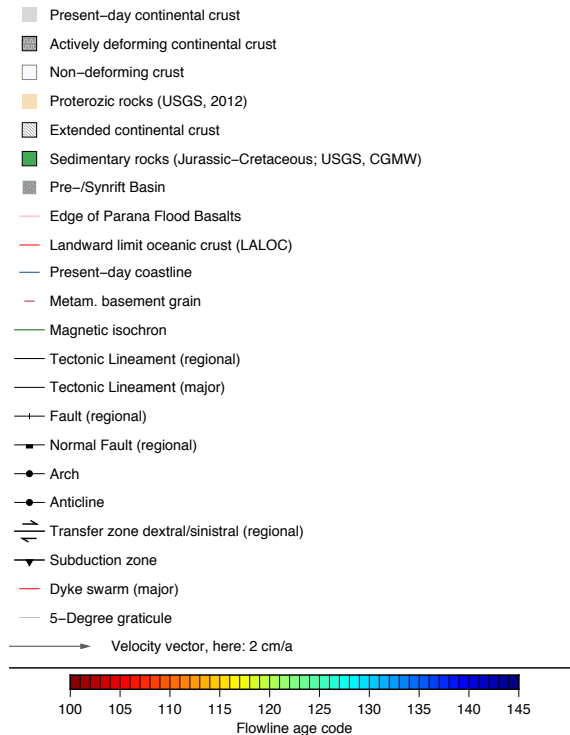


Fig. 21. Map legend for Figs. 12–20.