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Review and critical assessment on plate reconstruction models for the South Atlantic

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ABSTRACT

The breakup of a supercontinent is a vital process of global tectonic evolution. How exactly West Gondwana and Pangea broke up is a controversial topic with many unanswered questions and problems that the reconstruction models attempt to solve. Since the mid-20th century in the course of modeling the South Atlantic tectonic evolution, several works contributed to the understanding of South America and Africa pre-breakup configuration, early stages of rift, and the kinematic involved in the rupture. However, these plate reconstruction models present several misfit problems. Here we review and analyze such misfits based on compiled geophysical and geological data by reproducing and comparing 15 reconstruction models since the pioneering work of Bullard et al. (1965). The location and magnitude of gaps and overlaps in each model are significantly different, in which fit differences mostly result from the assumed deformation. Nevertheless, a few similarities can be drawn, such as the maximum implemented overlap in the Central segment of the South Atlantic. We recognize that the accurate quantification of intraplate deformation is a challenge in refined models, and argue that South Atlantic models that restore intraplate deformation using geological and kinematic constraints tend to achieve a better fit.

1. Introduction

The geometrical fit of the South America and Africa margins is one of the cornerstones of continental drift theory (du Toit, 1937; Wegener, 1912). The divergence between these two plates led to the formation of the South and Equatorial Atlantic oceans during Cretaceous times. Although their jigsaw fit seems to be perfect, precise pre-drift plate reconstruction faces several misfit problems.

The first quantitative attempt to fit together South American and African plates was made by Bullard et al. (1965) assuming rigid plate behavior and a synchronous opening of South and Equatorial Atlantic oceans. Following models were also based on the concept of fully rigid plates, which means that little to no deformation during or subsequent to the breakup has taken place in the interior of the continent. However, these reconstructions resulted in considerable misfits mostly in the Equatorial Atlantic and/or in the southern South Atlantic. The finer adjustment of these two parts was impossible to carry out without assuming a diachronic opening and intraplate deformation.

Plate models with distributed intraplate deformation have managed to solve the previous problems with poor adjustments. These models assume that the stress related to the northward propagation of the South Atlantic opening was probably accommodated in lithospheric discontinuities within South American and African plates. For instance, the Transbrasiliano lineament is a major structural element that has been suggested to accommodate intraplate deformation in the South American plate (Cordani et al., 2013; Moulin et al., 2010; Pérez-Gussinyé et al., 2007; Richetti et al., 2018). Another important feature widely considered to accommodate relative plate motion is the Benue Trough area, which documents extensional deformation between sub-plates in Africa (Burke and Dewey, 1974; Guiraud and Maurin, 1992).

Here we review the plate reconstruction models that depict pre-breakup configuration of South America and Africa in the Pangea framework. We reproduce these models and compare them based on standardized features derived from an extensive geological and geophysical data compilation of these continents. We will argue here that despite the significant evolution of plate reconstruction models

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since the pioneering work of Bullard et al. (1965), the South America and Africa pre-drift puzzle has not been completely solved yet.

2. Geological framework

Geological history records the repeated occurrence of continental collision and breakup which led to the hypothesis that continents periodically amalgamate into large landmasses called supercontinents (Dewey, 1969; Kearey et al., 2009; Wilson, 1966; Zhong et al., 2007). The dispersal of a supercontinent can be caused by upwellings and thermal insulation beneath them (Gurnis, 1988; Lenardic et al., 2011; Li and Zhong, 2009) or by the extensional stress in the lithosphere caused by subduction retreat (Bercovici and Long, 2014; Dal Zilio et al., 2018). These two hypotheses, however, are not mutually exclusive and one may be assisting the other to drive breakup.

The formation of Pangea started with the amalgamation of Gondwana in the late Cambrian (Rogers et al., 1995; Stampfli et al., 2013). These events, thoroughly described by Schmitt et al. (2018), are overlapped in time with the final breakup and dispersion of the previous supercontinent Rodinia at *ca.* 600 Ma (Cordani et al., 2009; Dalziel and Dewey, 2019; Li et al., 2008). By the time when it was fully consolidated, Gondwana comprised South America, Africa, Antarctica, Australia,

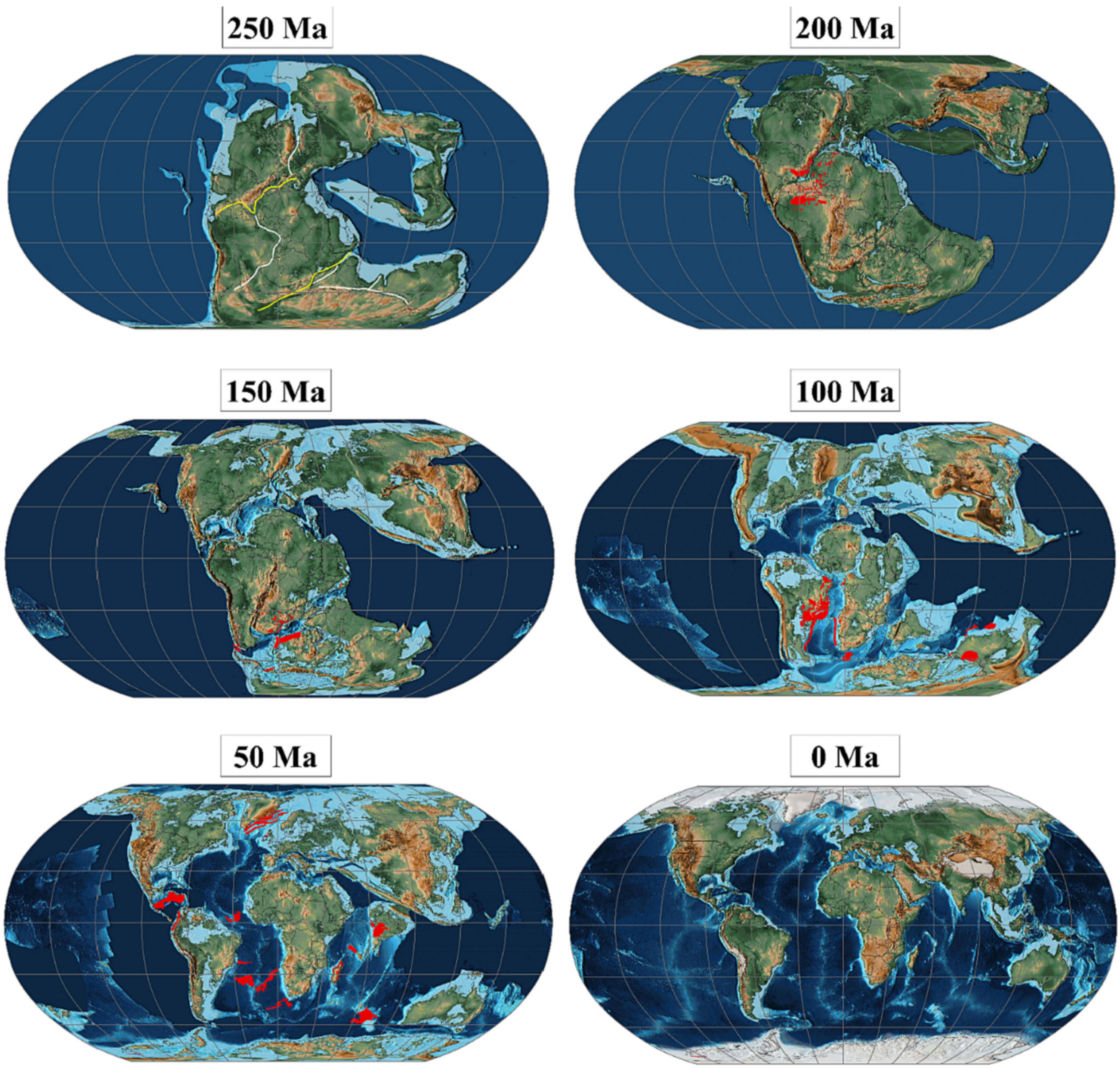

Fig. 1. Pangea dispersal using paleogeographic maps from PALEOMAP PaleoAtlas for GPlates (Scotese, 2016) in Robinson projection. Red polygons and lines are LIPs (Johansson et al., 2018) and Cretaceous Brazilian dikes (Pessano et al., 2020), respectively. 250 Ma paleogeographic reconstruction map includes main Jurassic-Triassic (yellow lines) and Cretaceous (white lines) break ups. 200 Ma reconstruction shows the emplacement of CAMP. 150 Ma reconstruction map exhibits the separation of East and West Gondwana and Karoo-Ferrar, Chon Aike and Dronning Maud Land volcanism. 100 Ma paleogeographic map shows West Gondwana breakup, with Paraná-Etendeka, EQUAMP, Cretaceous dikes in Brazil, Agulhas and São Paulo plateaus in early South Atlantic Ocean. It also depicts seafloor spreading between India and East Gondwana, and the emplacement of Kerguelen LIP and NW Australia basalts. 50 Ma map shows the emplacement of NAIP, Kerguelen plateau, Caribbean flood basalts, Seychelles LIP and Deccan traps in India. In the Atlantic region, the volcanic rocks include Sierra Leone Rise, Agulhas and Walvis ridges, Rio Grande Rise and Vitória-Trindade seamounts. Final map depicts present-day continents. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

India, Arabia, Madagascar and several smaller fragments, which corresponds to 64% of all current land areas above sea level (Torsvik and Cocks, 2013). Gondwana collided with Laurasia in the late Carboniferous (Frizon de Lamotte et al., 2015; Stampfli et al., 2013) to finally give form to Pangea, which continued to grow with the addition of other continental masses in Asia. The final assembly of Pangea took place in the Triassic after the amalgamation of Siberia, North and South China, Cimmerian and Tibetan blocks (Collins, 2003; Stampfli et al., 2013).

Pangea lasted until the end of Triassic, when its breakup and dispersal occurred asynchronously (Fig. 1) over old suture zones accompanied by extensive magmatic activity (*i.e.*, Large Igneous Provinces). The earliest breakup started with the separation between Gondwana and Laurentia in the Late Sinemurian (190 Ma, Labails et al., 2010; Sahabi et al., 2004) which formed the Central Atlantic Ocean. This rifting event is marked by the emplacement of the Central Atlantic Magmatic Province (CAMP) over a vast area of more than 10 million km^2 at *ca.* 201 Ma (Marzoli et al., 1999, 2018 and references therein). Tectonic extension within Gondwana in the Early Jurassic led to the final breakup of this supercontinent. This is depicted by the separation of East and West Gondwana between 188 and 170 Ma (Reeves et al., 2016) which culminated in the development of the Indian Ocean (Gaina et al., 2013; Reeves et al., 2016; Thompson et al., 2019) coevally with the major Karoo-Ferrar volcanism at *ca.* 183 (Ivanov et al., 2017; Jourdan et al., 2005).

Afterwards, the disassembly of Laurentia, East and West Gondwana took place resulting in smaller fragmented blocks. In this context, the first ocean floor was formed in the Weddell Sea at about 147 Ma after rifting between Antarctica and the southernmost part of South America (König and Jokat, 2006). This was followed by the Early Cretaceous breakup of West Gondwana which is synchronous to the disruption between India and Antarctica (Gaina et al., 2007; Gibbons et al., 2013).

The separation of South America from Africa led to seafloor spreading in the South Atlantic (Eagles, 2007; Heine et al., 2013; Moulin et al., 2010; Nürnberg and Müller, 1991; Owen-Smith et al., 2019; Pérez-Diaz and Eagles, 2014; Rabinowitz and LaBrecque, 1979; Torsvik et al., 2009). The initial rifting was accompanied by extensive magmatism of the Paraná-Etendeka LIP at *ca.* 134 Ma (Thiede and Vasconcelos, 2010), which is often associated to the Tristan da Cunha plume (Courtillot et al., 1999; Ernst and Buchan, 1997; Gibson et al., 1995; Milner and le Roex, 1996; Peate, 1997). We will not discuss the origin and source of the Paraná-Etendeka LIP in this paper, but we would like to point out some works that aim to find a causal relation between the emplacement of the LIP and/or the presence of the plume and the South Atlantic opening. Stica et al. (2014) reviewed the several propositions for the relationship between the Paraná-Etendeka emplacement and the rifting event – whether these were exactly contemporaneous or if the rift occurred shortly after the extrusion or even before. They argued that the short time period of LIP emplacement would minimize its effects as the driving force of breakup when compared to the long period of rifting as a whole. Using the concept of passive *vs.* active rifting, Frizon De Lamotte et al. (2015) considered that passive rifting occurred before the LIP emplacement to the south of the Paraná-Etendeka while post-emplacement active rifting dominated to the north. This hypothesis was corroborated by Owen-Smith et al. (2019) study in which paleomagnetic data for Etendeka volcanic succession was provided. Their results placed Paraná-Etendeka volcanism over a deep mantle plume shortly before the seafloor spreading in this region. Fromm et al. (2015) questioned the influence of the Tristan da Cunha plume in the South Atlantic opening. The authors' observations were inconsistent with an effective impact of the plume during the continental breakup and they further argued that the plume was present before the rifting, leaving a track of kimberlites and other associated rocks in the African craton. While it is still debatable whether or not the plume triggered the rifting, it has become progressively more evident that extension was underway before the extrusion. Darros de Matos (2021) pointed out that the South Atlantic rift propagated toward the Paraná-Etendeka LIP simultaneously from Northeast Brazil and Southern Argentina. According to this author, the boundary between these two competing and diachronous rift branches was the Proto Florianópolis Fracture Zone, which acted as a large-scale transfer zone.

The opening of the Equatorial Atlantic during the Aptian-Albian boundary (de Matos, 2000; Moulin et al., 2010; Szatmari et al., 1987; Ye et al., 2017) was a consequence of oblique divergence between the northern South America and West Africa (Basile et al., 2005; Heine and Brune, 2014; Mohriak and Rosendahl, 2003; Ye et al., 2017). A newly recognized LIP known as Equatorial Atlantic Magmatic Province (EQUAMP; Hollanda et al., 2019) at roughly 135–120 Ma probably contributed to this process. The opening of Equatorial Atlantic allowed the definitive sea water connection and circulation between the Central and South Atlantic oceans (Moulin et al., 2010; Pérez-Diaz and Eagles, 2014).

The onset of seafloor spreading between India and the remaining East Gondwana also occurred during the Early Cretaceous (Boger, 2011; Gaina et al., 2007; Gibbons et al., 2013; Peace et al., 2020; Ramana et al., 2001) with a subsequent high speed (18–20 cm/year) motion of the Indian plate (Kumar et al., 2007). It is still a matter of debate the link between this continental breakup and the Kerguelen LIP (Boger, 2011; Buiter and Torsvik, 2014; Gaina et al., 2007; Olierook et al., 2019). Later on, the breakup between Australia from Antarctica and Zealandia (Veevers, 2012; Williams et al., 2019) marked the end of the East Gondwana continent. As for Laurentia, the opening of the Northern Atlantic records multiple rift phases (Barnett-Moore et al., 2018; Matthews et al., 2016; Müller et al., 2016; Nirrengarten et al., 2018; Peace et al., 2020) that lasts from Permian to the Cenozoic and is beyond the scope of this work. Nevertheless, this event was accompanied by a massive magmatism known as the North Atlantic Igneous Province (NAIP; Buiter and Torsvik, 2014; Hansen et al., 2009; Horni et al., 2017; Storey et al., 2007; Wilkinson et al., 2017) with an initial eruption at *ca.* 63 Ma before the separation between Greenland and Europe (Buiter and Torsvik, 2014).

3. Data compilation

Reconstructing supercontinents is a complex process that requires many geodynamic concepts. When a reconstruction model is proposed, it must take into consideration geological, geophysical and tectonic factors in order to achieve a "best fit". Identifying and correlating piercing points and assessing the data used to constrain the plate motion is a powerful tool to evaluate these models. Therefore, a wide literature review regarding South American and African continental geology supported by the compilation of geological and geophysical data allowed us to generate thematic maps including data from gravity anomalies (Sandwell et al., 2014), bathymetry and topography (Amante and Eakins, 2009), seafloor age (Müller et al., 2016), magnetic anomalies (Maus et al., 2009; Seton et al., 2014), and geological maps on a global (Bouysse, 2014) and continental scale for South America (Cordani et al., 2016) and Africa (Thiéblemont et al., 2016). Additionally, the salt extension, fracture zones, inland faults and shear zones, LIPs and Continental-Ocean Boundaries (COB) data were compiled.

3.1. Major geological units

The major geological units include mobile belts, terranes and Archean nuclei, following the Cordani et al. (2016) division proposed for South America. The restoration of Pan-African-Brasiliano mobile belts geometry and their correlation is a fundamental step to reconstruct the architecture of ancient Gondwana (Trompette, 2000). Using geological and tectonic maps of South America (Cordani et al., 2016), Africa (Thiéblemont et al., 2016) and Gondwana (Schmitt et al., 2018), we produced a simplified map (Fig. 2) of these geological units using a unified legend for both continents. These elements were also used when reproducing the several reconstruction models in order to compare

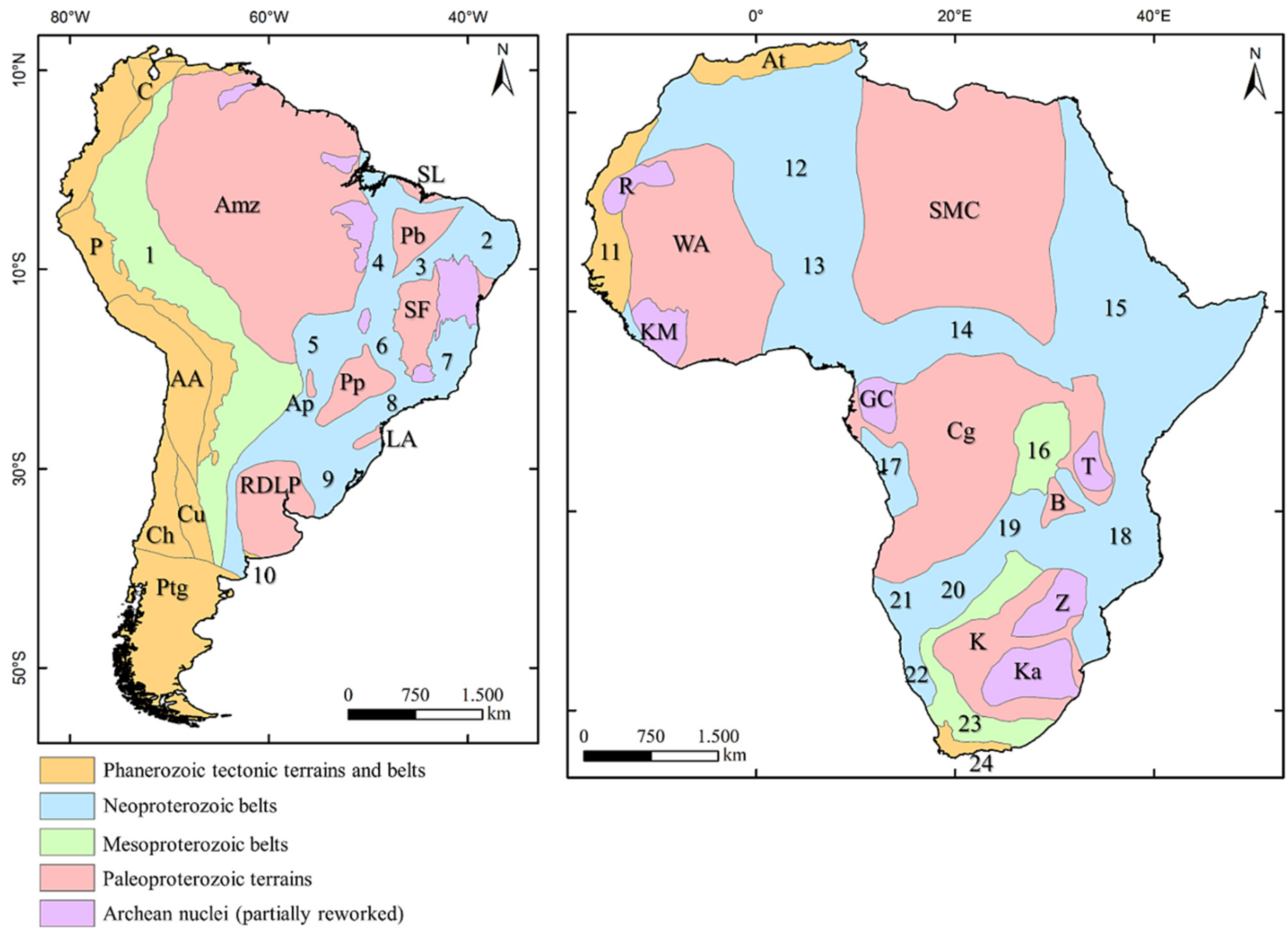

Fig. 2. Major geological units of South America and Africa. Abbreviations correspond to Archean nuclei and Paleoproterozoic and Phanerozoic terranes while numbers refer to mobile belts. South America abbreviations – Amz: Amazonian Craton; SL: São Luís Craton; Pb: Parnaíba block; SF: São Francisco Craton; Pp: Paranapanema Block; Ap: Rio Apa Block; LA: Luís Alves Craton; RDLP: Rio de la Plata Craton; Ptg: Patagonia; Ch: Chilenia; Cu: Cuyania; AA: Arequipa-Antofalla; P: Paracas; C: Chibcha. Africa abbreviations – At: Atlas; R: Reguibat; KM: Kenema-Man; WA: West African Craton; SMC: Saharan Metacraton; Cg: Congo Craton; GC: Gabon-Chaillu; T: Tanzania; B: Bangweulu; K: Kalahari Craton; Z: Zimbabwe; Ka: Kaapvaal. Mobile Belts – 1: Sunsás; 2: Borborema Province; 3: Rio Preto Belt; 4: Araguaia Belt; 5: Paraguay Belt; 6: Brasília Belt; 7: Araçuaí Belt; 8: Ribeira Belt; 9: Dom Feliciano Belt; 10: Sierra de la Ventana Belt; 11: Mauritanides; 12: Hoggar Belt; 13: Dahomey Belt; 14: Oubanguides Belt; 15: East African Belt; 16: Kibaran Belt; 17: West Congo Belt; 18: Lurio Belt; 19: Zambezi Belt; 20: Damara Belt; 21: Kaoko Belt; 22: Gariep Belt; 23: Namaqua-Kibaran; 24: Cape Fold Belt.

them.

3.2. Sedimentary basins

Sedimentary basins are key to understanding the evolution of a supercontinent as they record changes in climate and tectonic environment. Pioneering stratigraphic correlations between Paleozoic South America and Africa basins were used by du Toit (1937) to support the proposal of a unified continent. Rift-related basins are especially useful to estimate tectonic extension (Heine et al., 2008; Heine et al., 2013) during the opening process and can provide key information on the accommodation of the intraplate deformation. This is achieved by calculating total tectonic subsidence using the thickness and average density of sediments in each basin as demonstrated by Heine et al. (2008, 2013). However, values obtained using this methodology are likely to be an overestimation of actual extension, as it is based on total sediment thickness, measured orthogonal to major basin/rift axis (Heine et al., 2013).

The extent of Aptian salt is also important to correlate the margins (Chaboureau et al., 2012; Kukla et al., 2018; Lentini et al., 2010; Rowan, 2014; Torsvik et al., 2009). A map of sedimentary basins (Fig. 3) with ages ranging from the Proterozoic to Cenozoic was produced based on geological maps (Bouysse, 2014; Cordani et al., 2016; Thiéblemont et al., 2016) with additional data from Robertson (2019) sedimentary basins of the world map.

3.3. Structural controls and fracture zones

The fracture zones found in the South Atlantic Ocean were formed during seafloor spreading and are defined as an extension of transform faults where active strike-slip motion occurs (Hall and Gurnis, 2005). They have been proved to be powerful constraints of the relative motion between two plates (Cande et al., 1988; Eagles, 2007; Francheteau and Pichon, 1972; Jones, 1987; Moulin et al., 2010; Rabinowitz and LaBrecque, 1979). During the early stages of continental breakup, their formation may be influenced by pre-existing crustal weaknesses inherited from basement structures (Vasconcelos et al., 2019 and references therein). These features along with inland faults can help understand intraplate deformation due to their potential of accommodating deformation produced in the breakup process. Moulin et al. (2010) has proposed a division of the South Atlantic into four segments bounded from north to south by Marathon, Ascension, Rio Grande and Agulhas-Falkland fracture zones. These are the Equatorial (here also named Equatorial Atlantic), Central, Austral and Falkland segments. Inland, one of the most important structures is the Transbrasiliano-Kandi lineament, a continental shear zone that cuts

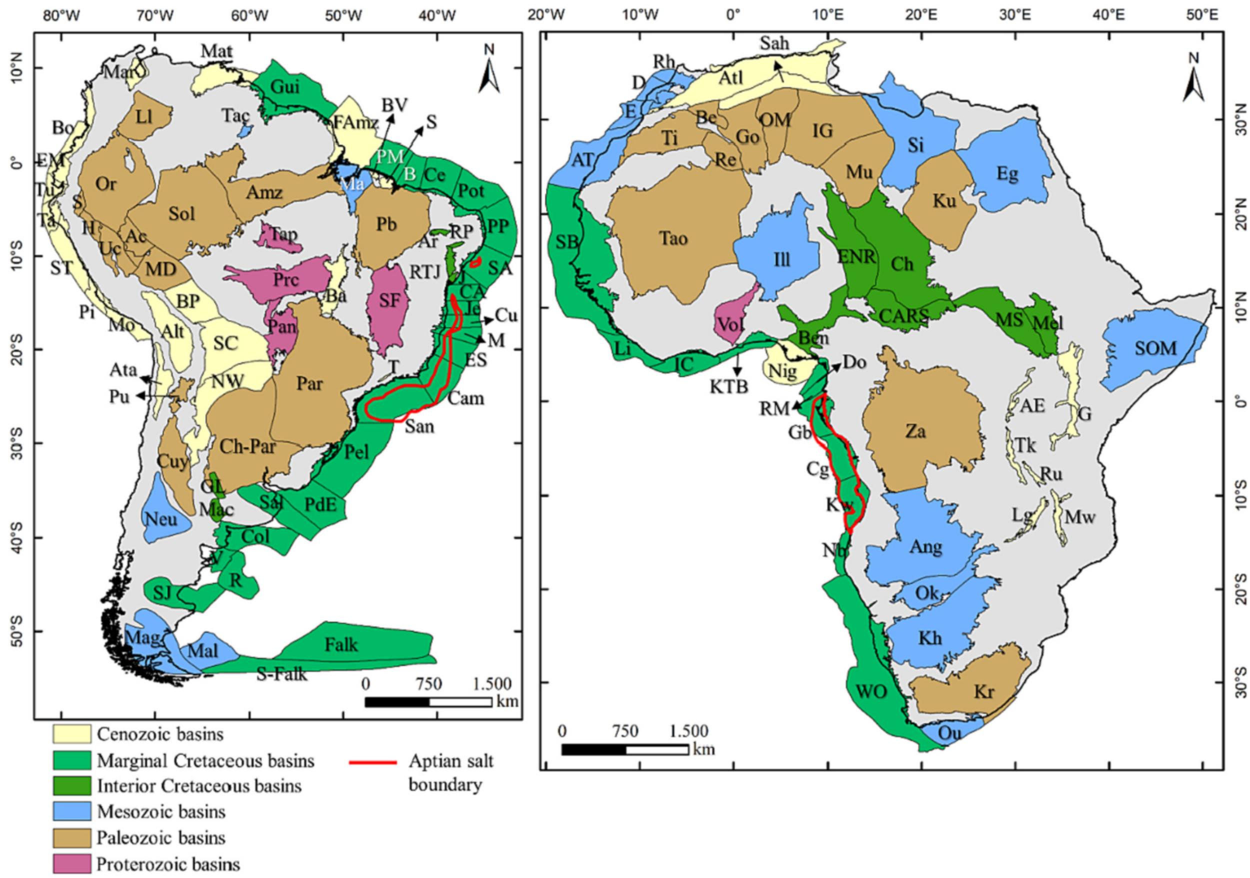

Fig. 3. Main sedimentary basins of South America and Africa, colored by age. South American basins - Ac: Acre; Alt: Altiplano; Amz: Amazonas; Ar: Araripe; Ata: Atacama; B: Barreirinhas; Ba: Bananal; Bo: Borbon; BP: Beni Plain; BV: Bragança-Viseu; CA: Camamu-Almada; Cam: Campos; Ce: Ceará; Ch-Par: Chaco-Paraná; Col: Colorado; Cu: Cumuruxatiba; Cuy: Cuyo; EM: Esmeraldas - Manabi; ES: Espírito Santo Falk: Falkland; FAmz: Foz do Amazonas; GL: General Levalle; Gui: Guianas; H: Huallaga; J: Jacuípe; Je: Jequitinhonha; Ll: Llanos; M: Mucuri; Ma: Marajó; Mac: Macachín; Mag: Magallanes; Mal: Malvinas; Mar: Maracaibo; Mat: Maturin; MD: Madre de Dios; Mo: Mollendo; Neu: Neuquen; NW: Northwest; Or: Oriente; Pan: Pantanal; Par: Paraná; Pb: Parnaíba; PdE: Punta del Este; Pel: Pelotas; Pi: Pisco; PM: Pará-Maranhão; Pot: Potiguar; PP: Pernambuco-Paraíba; Prc: Parecis; Pu: Puna; R: Rawson; RP: Rio do Peixe; RTJ: Recôncavo-Tucano-Jatobá; S: Santiago; S: São Luis; SA: Sergipe-Alagoas; Sal: Salado; San: Santos; SC: Santa Cruz; SF: São Francisco; SJ: San Jorge; Sol: Solimões; ST: Salaverry-Trujillo; T: Taubaté; Ta: Talara; Tac: Tacutu; Tap: Tapajós; Tu: Tumbes; Uc: Ucayali; V: Valdes. African basins – Ang: Angola; AT: Aaiun-Tarfaya; Atl: Atlas; Be: Bechar; Ben: Benue; CARS: Central Africa Rift; Cg: Congo; Ch: Chad; D: Doukkala; Do: Douala; E: Essaouira; Eg: Egypt; ENR: Eastern Niger Rift; Gb: Gabon; Go: Gourara; IC: Ivory Coast; IG: Illizi-Ghadames; Ill: Illumeden; Kh: Kalahari; Kr: Karoo; KTB: Keta-Togo-Benin; Ku: Kufrah; Kw: Kwanza; Li: Liberia; Mel: Melut; MS: Mugglad-Sudd; Mu: Murzuq; Nb: Namibia; Nig: Niger delta; Ok: Okavango; OM: Oued Mya; Ou: Outeniqua; Re: Reggane; Rh: Rharb; RM: Rio Muni; Sah: Sahara; SB: Senegal-Bove; Si: Sirte; SOM: Somali-Ogaden-Mandera Lugh; Tao: Taoudenni; Ti: Tindouf; Vol: Volta; WN: White Nilo; WO: Walvis-Orange; Za: Zaire. East African Rifts: AE: Albert-Edward; G: Gregory; Lg: Luanga; Mw: Malawai; Ru: Rukwa; Tk: Tanganyika. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

through South America and Africa, formed during Gondwana assembly (Cordani et al., 2013; Ganade et al., 2016). This lineament is regarded as a piercing point by some authors (*e.g.* De Wit et al., 2008; Richetti et al., 2018). A map of fracture zones (Matthews et al., 2011; Moulin et al., 2010) and inland faults and shear zones (Cordani et al., 2016; Thiéblemont et al., 2016) was produced based on these available data (Fig. 4).

3.4. Large igneous provinces

The fragmentation of Gondwana was accompanied by several magmatic episodes (Buiter and Torsvik, 2014; Peace et al., 2020). Large igneous provinces coincide with major lithosphere-scale shear movements and aborted rifts (Peace et al., 2020) and are to some degree related to breakup processes. Identifying these great events is a fundamental step to establish the geodynamic evolution of continental masses, and therefore, it is an important tool in plate reconstructions. A map containing major LIPs (Johansson et al., 2018; Whittaker et al., 2015) and dikes (Jessell et al., 2015; Pessano et al., 2020) is shown on Fig. 5, with ages spanning from Triassic to Paleogene.

3.5. Continent-ocean boundary

The continent-ocean boundary (COB) is used to distinguish these two crustal types and its delineation is based on interpretation of geophysical data (Blaich et al., 2011; Gaina et al., 2013; Heine et al., 2013; Macdonald et al., 2003; Müller et al., 2016; Nürnberg and Müller, 1991; Rabinowitz and LaBrecque, 1979; Richetti et al., 2018; Schmitt et al., 2016; Seton et al., 2012; Torsvik et al., 2009). However, its use as a simple linear feature between continental and oceanic crust is often an oversimplification (Eagles et al., 2015), so that the COB is better described as a finite-width continent-ocean transition zone (COT or COTZ). In some cases, this transition is adopted to define the part of the lithosphere located between the stretched continental crust and the oceanic crust formed by seafloor spreading (Blaich et al., 2011). Nevertheless, establishing the location of the COB as a line on large-scale maps can bring valuable insight into plate reconstructions, and it can be used as a marker to test or determine rotation parameters for such models (*e.g.*, Moulin et al., 2010; Torsvik et al., 2009).

Eagles et al. (2015) have published a thorough review on this boundary location worldwide and their data on the South Atlantic was

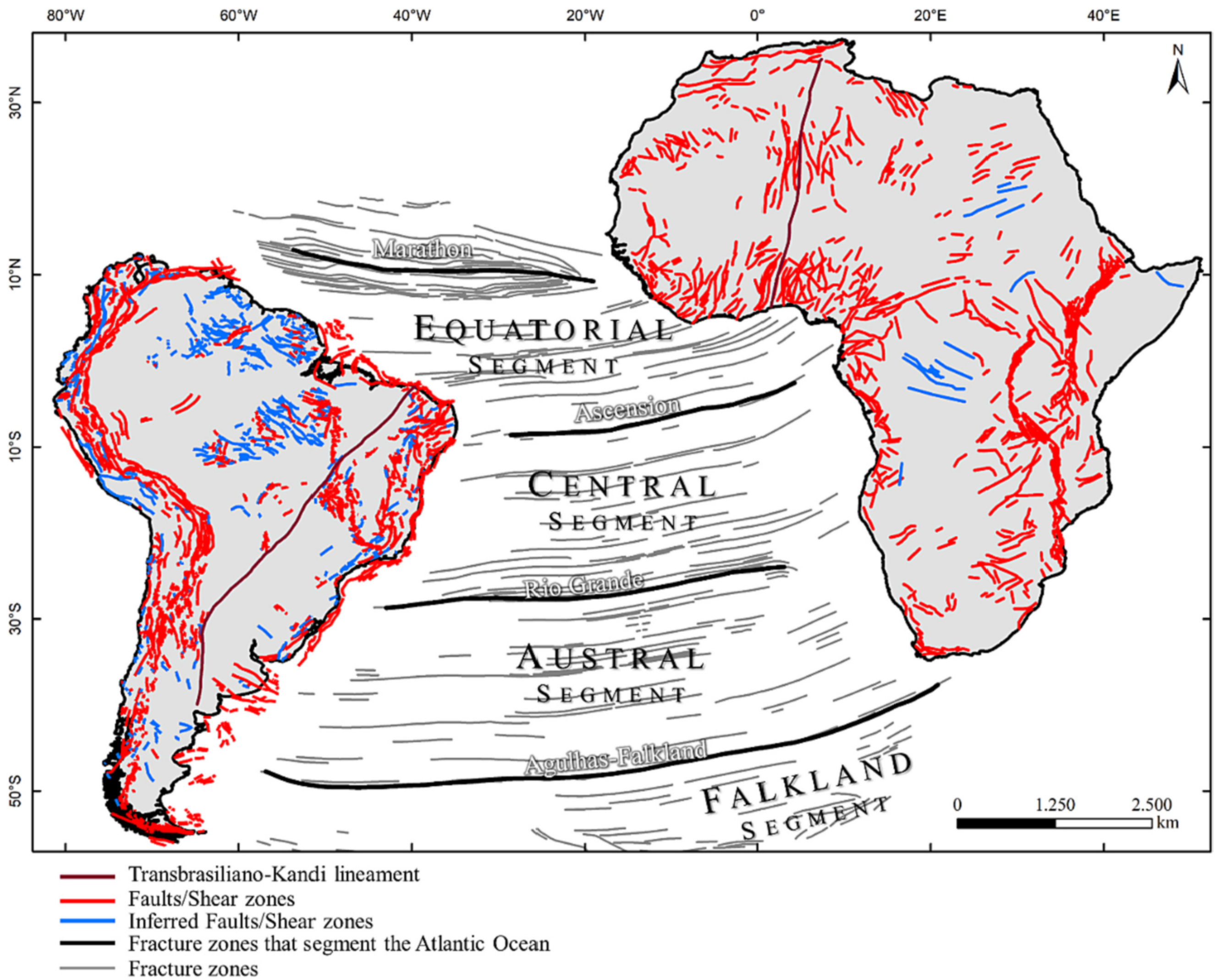

Fig. 4. Faults, shear zones and fracture zones of South America, Africa and South Atlantic Ocean. Main fracture zones that segment the South Atlantic according to Moulin et al. (2010) are named.

incorporated into our compilation (Fig. 6). The data show smaller uncertainties for the COBs in the equatorial segment, while its largest variability is found in the central segment. This is mainly due to interpretation, as the nature of the COT in the central segment is heavily debated. The crust at the COT domain in the central segment has been defined as proto-oceanic crust (Mohriak and Rosendahl, 2003), as exhumed middle/lower continental crust (Aslanian et al., 2009), and as exhumed mantle (Péron-Pinvidic et al., 2017; Unternehr et al., 2010). Along the Camamu and Espírito Santos margins, Blaich et al. (2011) interpreted the COT as characterized by rotated continental fault blocks and wedge-shaped synrift sedimentary sequences. Heine et al. (2013) proposed the "landward limit of the oceanic crust" (LaLOC) as a boundary which delimits relatively homogeneous oceanic crust oceanward from either extended continental crust or exhumed continental lithospheric mantle landward or SDRs where an interpretation of the Moho and/or the extent of continental crust is not possible.

In order to evaluate and compare the misfits of the several reconstruction models, we had to pick the most fitting and up to date continent-ocean boundary and reconstruct this feature for each model. The "landward limit of oceanic crust" proposed by Heine et al. (2013) seemed the most appropriate boundary to adopt in the reconstructions, considering the authors' argument of the usefulness of the LaLOC in areas of the South Atlantic where classic COB cannot be easily defined such as the oceanward boundary of the Santos Basin, distal parts of the Kwanza Basin or along the conjugate magmatic margin in the southern part of the South Atlantic. Fig. 7 shows margin cross sections based on Blaich et al. (2011) and modified from Heine et al. (2013), where a comparison of COB, LaLOC, and a conservative estimation of the limit of continental crust is made.

3.6. Magnetic picks

Oceanic magnetic anomalies are one of the best spatiotemporal constraints, and have helped to determine the timing of continental breakup, and to reconstruct paleopositions (*e.g.,* Granot and Dyment, 2015; Moulin et al., 2010; Nürnberg and Müller, 1991; Rabinowitz and LaBrecque, 1979). Their identification is based on visual comparison of synthetic and observed magnetic anomaly profiles (Gee and Kent, 2007), and as such is subjected to interpretation of data. This is illustrated by a collection of magnetic picks data from Seton et al. (2014) repository (Fig. 8). However, as we will further discuss, the relative motion between South American and African plates, as well as the onset of seafloor spreading are still heavily debated and remains poorly resolved due to the lack of reversal-related magnetic anomalies during the Cretaceous Normal Superchron (CNS; Cande and Kent, 1995; Granot et al., 2012; Granot and Dyment, 2015; Moulin et al., 2010).

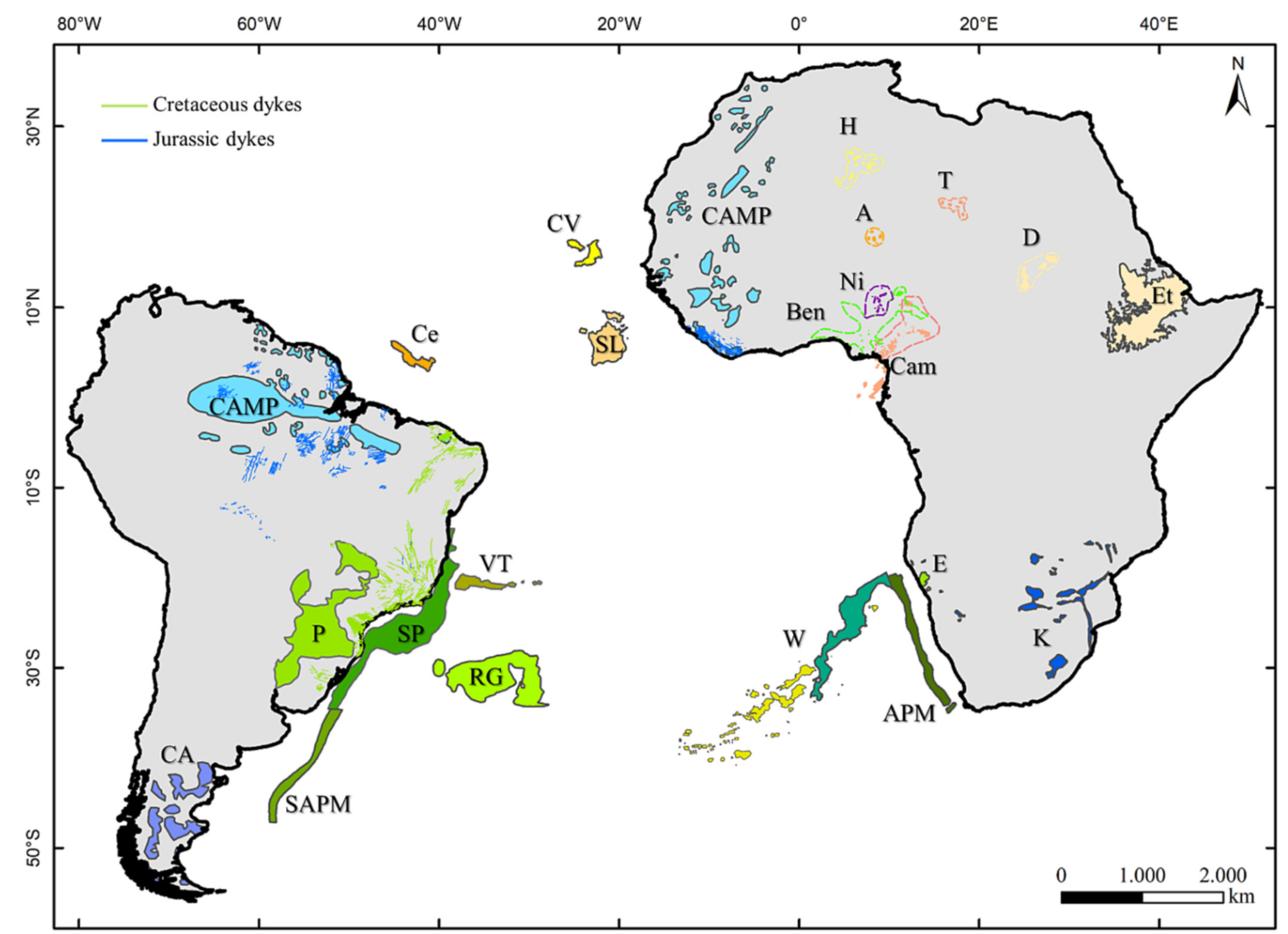

Fig. 5. Large Igneous Provinces and dyke swarms in South America, Africa and South Atlantic Ocean. Color grades correspond to various magmatism ages. Shades of yellow are Neogene; orange: Paleogene; green: Cretaceous; blue: Jurassic; and purple: Triassic. Abbreviations – A: Air; APM: African Passive Margin; Ben: Benue; CA: Chon Aike; Cam: Cameroon; CAMP: Central Atlantic Magmatic Province; Ce: Ceará Rise; CV: Cape Verde; D: Darfur; E: Etendeka; Et: Ethiopia; H: Hoggar; K: Karoo; Ni: Nigeria; P: Paraná; RG: Rio Grande Rise; SAPM: South American Passive Margin SL: Sierra Leone Rise; SP: São Paulo Plateau; T: Tibesti; VT: Vitória-Trindade seamounts; W: Walvis Ridge. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4. Methodology

We compiled several reconstruction models published throughout the last decades and selected fifteen of those based on their relevance and available data to be reproduced and analyzed. Integration of data through GPlates v. 2.2.0 (Müller et al., 2018) allowed us to replicate the models. The GPlates plate-motion focuses on relative motion described by total reconstruction poles. This requires the motion parameters of each moving plate in relation to a fixed plate at a point in time. These plates are identified by a Plate ID, which is also assigned for the compiled features partitioned into tectonic polygons on each plate.

We opted anchoring the African plate (South Africa when further divided) due to its stability for the past 200 million years and its central position within Pangea (Burke and Torsvik, 2004; Müller et al., 2016; Torsvik et al., 2008). As for the point in time, 130 Ma was the chosen time to depict the pre-rift configuration for West Gondwana. The motion of any given plate relative to Africa is defined by a rotation pole (a finite Euler rotation) which is described by its latitude, longitude and angle of rotation. When necessary, the rotation poles were recalculated for the proposed anchored plate and/or for the proposed time using GPlates functionality of total reconstruction poles. The compiled data is summarized in Table 1, which lists the age, motion parameters and plates of each reconstruction model.

The reconstructed data was then exported as a shapefile to produce maps for each model. Major geological units were standardized in order to enable a good comparison between models. Regarding the continent-ocean boundary, we point out that although the original COB is an important parameter in its corresponding model, no large discrepancy was found between the original reconstruction and our reproduction of those from Heine et al. (2013) boundaries. As there is an equal probability of any of the COB estimates being correct within uncertainties, then both scenarios can be regarded as equally plausible as shown in Eagles et al. (2015). For that reason, we opted for using the continent-ocean boundary proposed by Heine et al. (2013) in all reconstructions, which allowed us to compare the extent of gaps and overlaps from the different models using the same feature. Measurements of misfits were made in ArcMap 10.3 and are represented by different color ramps for gaps and overlaps with variation in color every 10 km.

5. Results

Although it remains controversial how South America and Africa broke up, several reconstruction models strive to solve this problem. The first attempts of reconstructing West Gondwana were based on rigid plates without any intraplate deformation (*e.g.* Bullard et al., 1965; Keith Martin et al., 1981; Rabinowitz and LaBrecque, 1979; Vink, 1982). These result in overlaps and gaps of reconstructed continental blocks in which overlaps represent areas followed by extension and gaps

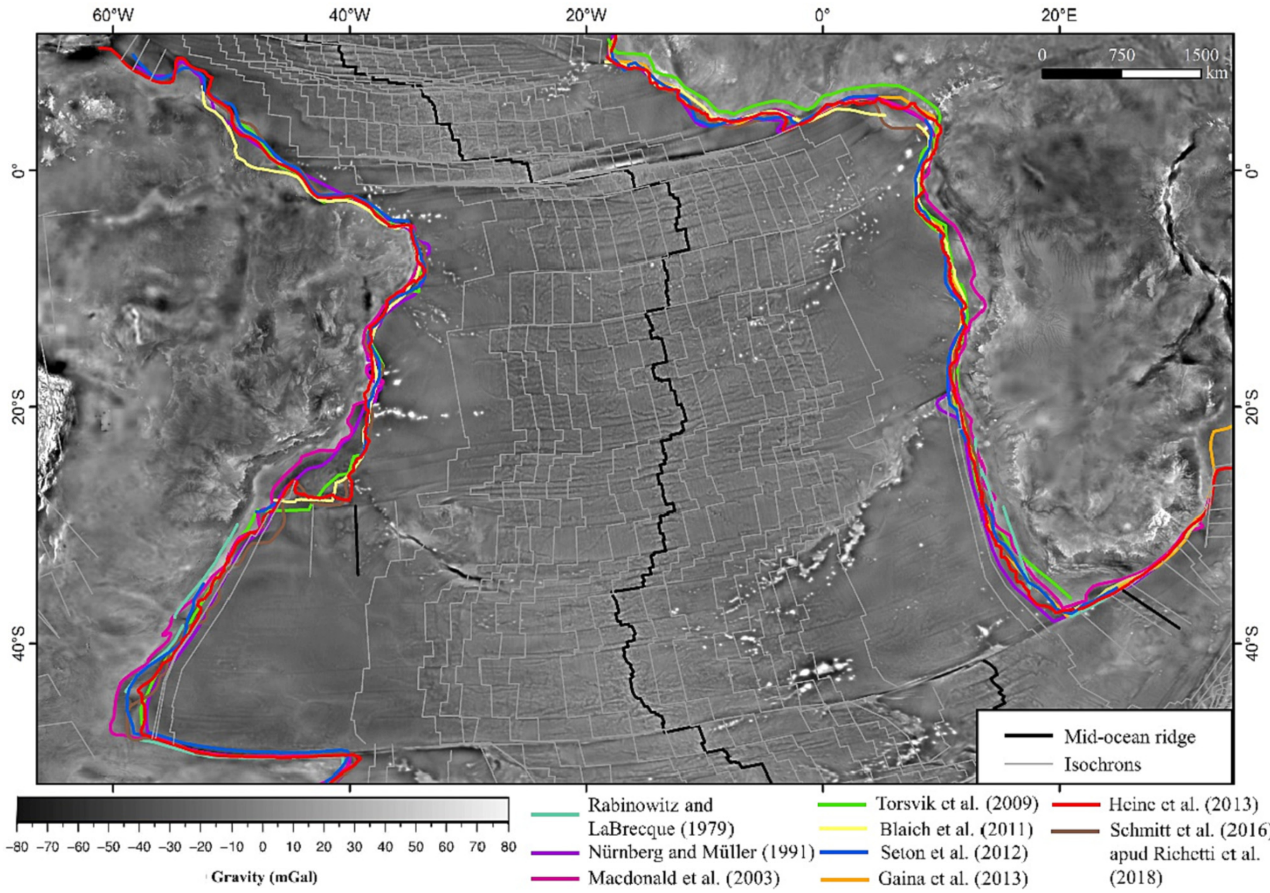

Fig. 6. Compiled continent-ocean boundaries of South America and Africa in free-air anomaly map (Sandwell et al., 2014). Mid-ocean ridge and isochron data from Seton et al. (2020).

characterize regions of subsequent compression (Müller et al., 2019).

The pioneering work of Bullard et al. (1965) proposed a rigid plate model based on statistical reconstruction (Figs. 9a, 10a). The fitting was achieved using numerical methods with a least square criterion. The model shows many overlaps and gaps along the plate margins and the proposed fit did not include the Falkland Plateau as noted by Keith Martin et al. (1981). Nevertheless, this iconic reconstruction was a major breakthrough in plate tectonics and was widely accepted for many years.

There is now a general consensus regarding the diachronic opening of the South Atlantic, but this was not always the case. Initial studies proposed a synchronous opening (Mascle and Sibuet, 1974; Sibuet and Mascle, 1978; Smith and Briden, 1977) that was initially refuted by the work of Rabinowitz and LaBrecque (1979). The authors noted that rifting in the austral segment of the South Atlantic occurred earlier than in the Equatorial Atlantic. Therefore, their work proposed an evolution of the South Atlantic with different separation rates for *ca.* 135–130 and *ca.* 111–107 Ma indicated by a change in the rotation poles. Rabinowitz and LaBrecque (1979) reconstruction (Figs. 9b, 10b) is based on the fit of gravity and magnetic anomalies interpreted by the authors in the African and Argentine margins. This results in mostly overlaps along the margins with gaps in the Demerara and Guinea plateaus region.

Following the concept of fully rigid plates, Keith Martin et al. (1981) proposed a reconstruction that aimed at retaining a close fit of the Falkland Escarpment and the Agulhas margin while trying to solve overlap problems from Rabinowitz and LaBrecque (1979) model. Their fit (Figs. 9c, 10c) was constrained by three piercing points: (1) the eastern and western boundaries of Outeniqua Basin in South Africa and the Falkland Plateau Basin; (2) transcurrent faults and mylonite belts of Foumban in West Africa and Pernambuco in Northeast Brazil; (3) the northern tectonic front of Cape Fold Belt and the "morphological feature on the Falkland Plateau" that is now known as the Sierra de la Ventana Fold Belt. Their reconstruction results in overlaps along the conjugated margins except in the Demerara and Guinea plateaus where a smaller than 50 km gap is observed. The authors recognized that in order to produce an accurate reconstruction, second-order intraplate movements that constitute a breakdown of the assumption of rigid plate behavior must be accounted for.

Vink (1982) argued that these previous reconstructions were based on the assumption that no extension occurs within the continent during the rift process, meaning that the continents rift without any distortion. Therefore, the author proposed a propagating rift model for continental breakup in which the continental edges have undergone variable amounts of distributed extension. In the South Atlantic, this model results in an apparent overlap that increases in the northward direction (Figs. 9d, 10d).

As we will further discuss, the problems derived from the premise of fully rigid plates are difficult to solve. The assumption of intraplate deformation allowed a new approach in reconstruction models. This was first explored by Burke and Dewey (1974) with the remarkable inquiry on the existence of two plates in Africa during the Cretaceous. Their studies suggested that from *ca.* 125 to 80 Ma Africa did not behave as a single rigid plate which led them to propose a major division within Africa at the Benue Trough.

Following this proposal, Pindell and Dewey (1982) reconstructed western Pangea focusing on the evolution of the Caribbean region. For the purposes of the present work, we will address only South America and Africa configuration (Figs. 9e, 10e). Thus, in the South Atlantic, Pindell and Dewey (1982) proposed an additional constraint in the rigid model of Rabinowitz and LaBrecque (1979) in order to generate left-lateral motion accompanied by an extensional component across the

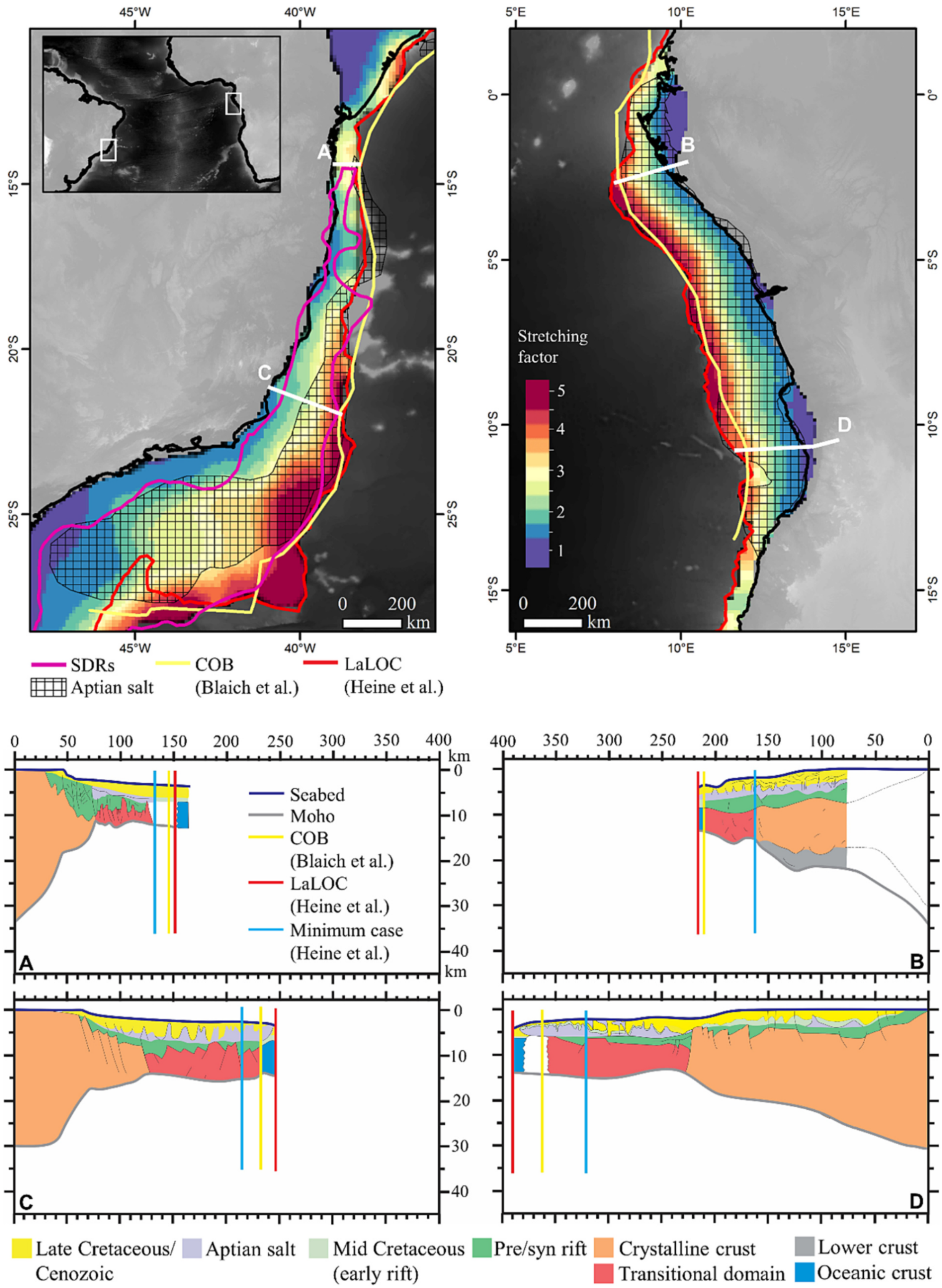

Fig. 7. Central South Atlantic conjugate margins, showing the location of cross sections, Aptian salt, SDRs and stretching factor (Haas et al., 2022). Margin cross sections are based on Blaich et al. (2011) and modified from Heine et al. (2013). LaLOC is the landward limit of oceanic crust (maximum estimate; Heine et al., 2013); COB is the continent-ocean boundary based on Blaich et al. (2011); and the minimum case represents a conservative estimation of limit of continental crust (Heine et al., 2013).

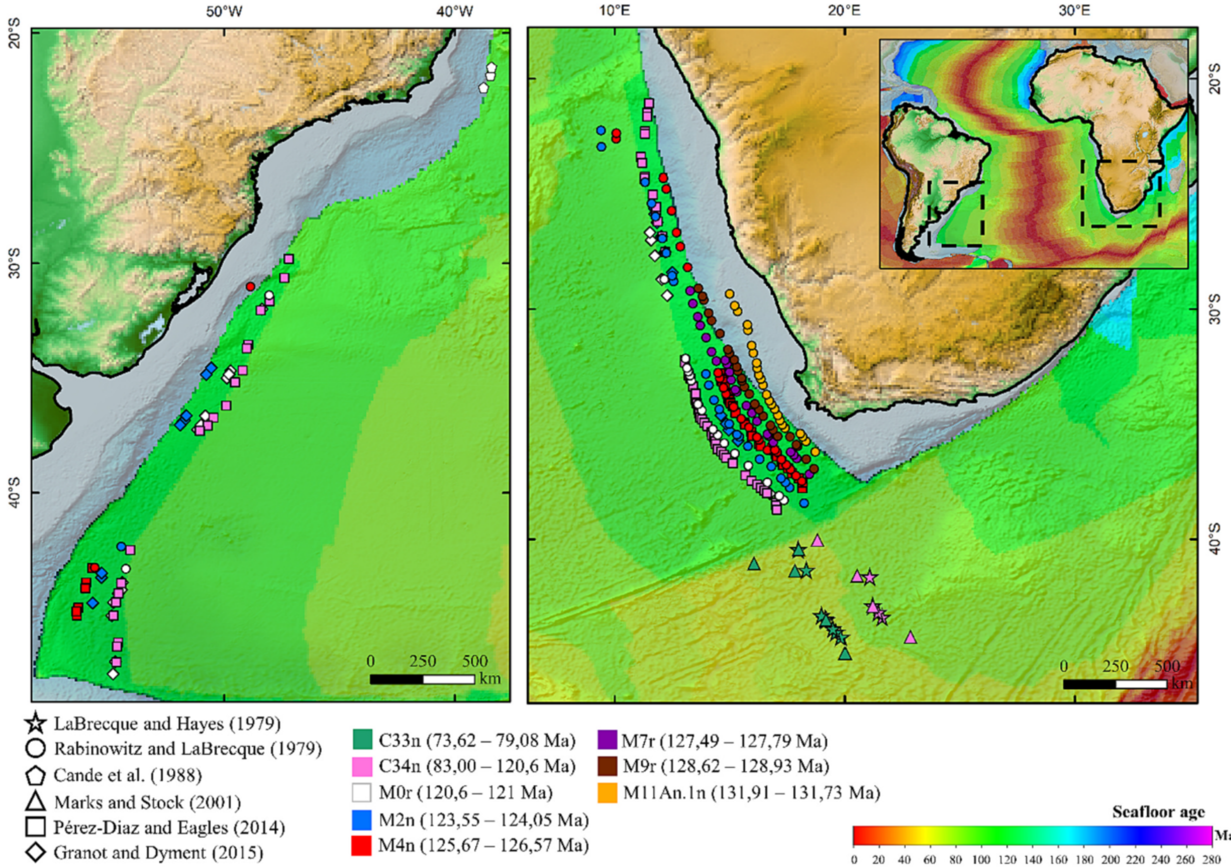

Fig. 8. South Atlantic magnetic picks compilation, chron colored based on Gee and Kent (2007) timescale. Seafloor age (Müller et al., 2016) and continental topography (Amante and Eakins, 2009) is shown.

Benue Trough. This results in a 200 km intraplate gap in northern Africa between the Northwestern and Southeastern blocks, and substantial overlaps in the conjugated margins.

On the other hand, Curie (1984) proposed a boundary within the South American plate ranging from the Rio Grande Rise to the Andean Cochabamba-Santa Cruz bend. This division is further supported by Unternehr et al. (1988) on the grounds that it adequately explains the initial opening of the South Atlantic. This reconstruction (Figs. 9f, 10f) results in several gaps in the conjugated margins and it implies a 350 km strike-slip movement between the Northern and Southern South American blocks.

Still exploring the African division, Fairhead (1988) on the basis of geological and geophysical studies in West Africa attempted to define the fault geometry of the West and Central African rift systems. The author provides evidence for the link between the development of these rift systems and the opening of Equatorial and South Atlantic oceans. Similarly, Guiraud and Maurin (1992) described the structure and evolution of the rift basins in the West and Central Africa rift systems. The authors proposed three subdivisions for the African plate with boundaries corresponding to major fracture and rift zones such as the Benue Trough, the Gulf of Guinea, Central African and Trans-Saharan fracture zones and the Easter Niger and Sudan-Kenya rifts. These are the Western, Arabian-Nubian and Austral blocks. Unfortunately, it was not possible to reproduce these models as they lack information regarding the pole used in the reconstructions.

Through a magnetic anomaly, altimetry and geologic database, Nürnberg and Müller (1991) proposed a fit-reconstruction (Figs. 9g, 10g) assuming the combination of complex rift and strike-slip movements. Their work was the first to describe the South Atlantic evolution from fit position to present day configuration, proposing a stepwise northward propagation of the South Atlantic rift and intraplate deformation in both continents. They derived the fit starting in the Equatorial Atlantic in order to avoid any gaps between the Guinea and Demerara plateaus and applied a rotation closing the Benue Trough. Therefore, the authors assumed movements along the Paraná-Chacos Basin deformation zone, within South American marginal basins (Salado and Colorado) and along the Benue Trough/Niger Rift system. The South American plate is divided into four blocks: South America, Paraná, Colorado and Salado, while the African plate is divided into two: Northwestern and South Africa. Nürnberg and Müller (1991) reconstruction results in intraplate overlaps in South America and an 80 km strike-slip movement between the Paraná and South America blocks. In their model, the austral segment of the South Atlantic resulted in gaps while the central and equatorial segments present overlaps.

Several works followed Nürnberg and Müller (1991) proposal (*e.g.*, Dalziel, 1997; König and Jokat, 2006; Lawver et al., 1998; Macdonald et al., 2003; Torsvik et al., 2008). These authors used rotation poles in their reconstructions that are close to those of Nürnberg and Müller (1991). Consequently, their models exhibit similar misfits in the South Atlantic.

On a different approach, Schettino and Scotese (2005) proposed synthetic apparent polar wander paths for North America, South America, Eurasia, India, Central Africa, Australia and Antarctica. For the purposes of the present work, we will focus on the South America and Africa reconstruction (Figs. 9h, 10h). Their tectonic model divides the South American plate into four blocks: Brazilian Craton, Paraná, Patagonia and Salado and Africa into five blocks: Northwestern Africa, Northeastern Africa, Nubia, Somalia and Central Africa. As the authors do not explicit the rotation poles for the Nubian block in their work, we assumed it to be fixed with Central Africa. Schettino and Scotese (2005) fit takes into account the deformation in Africa proposed by Guiraud and Maurin (1992) which is noticed by the intraplate overlap between

Table 1
Finite rotation of each reproduced plate reconstruction model by author in chronological order. In cases where calculation of reconstruction pole was necessary, either because age or fixed plate was not according to standardized parameters, original data given by the authors are in parenthesis.

Model	Age (Ma)	Latitude	Longitude	Angle of rotation	Moving plate	Fixed plate
Bullard et al. (1965)	130	44	−30.6	57	South America	Africa
Rabinowitz and LaBrecque (1979)	130	45.5	−32.2	57.5	South America	Africa
Keith Martin et al. (1981)	130	46.75	−32.65	56.4	South America	Africa
Vink (1982)	130?	47	−33.8	58	South America	Africa
Pindell and Dewey (1982)	130	49.67 (55.1)	−31.3 (−35.7)	56.73 (50.9)	South America	SE-Africa (W-Africa)
	130	19 (19)	2 (2)	8 (−8)	W-Africa (SE-Africa)	SE-Africa (W-Africa)
Curie (1984)	130	45.5	−32.2	55.5	S-South America	Africa
	130	52.8	−33.2	50.6	N-South America	Africa
Nürnberg and Müller (1991)	130 (131.5)	50.0 (50.0)	−32.5 (−32.5)	54.45 (55.08)	South America	S-Africa
	130 (131.5)	49.4 (49.4)	−34.7 (−34.7)	54.87 (55.5)	Paraná	S-Africa
	130 (131.5)	48.9 (48.9)	−35.6 (−35.6)	54.97 (55.6)	Salado	S-Africa
	130 (131.5)	48.9 (48.9)	−36.2 (−36.2)	55.16 (55.8)	Colorado	S-Africa
	130 (131.5)	16.5 (16.5)	6.7 (6.7)	1.00 (1.15)	NW-Africa	S-Africa
Schettino and Scotese (2005)	130 (140)	46.75 (46.75)	−32.65 (327.35)	52.37 (56.4)	Brazilian Craton	Central Africa
	130 (140)	46.59 (46.59)	−32.58 (327.42)	52.88 (56.95)	Paraná	Central Africa
	130 (140)	44.61 (44.61)	−32.46 (327.54)	53.92 (58.07)	Patagonia	Central Africa
	130 (140)	44.63 (44.63)	−32.52 (327.48)	53.56 (57.68)	Salado	Central Africa
	130 (200)	61.18 (61.18)	153.81 (153.81)	−0.71 (−1.1)	Somalia	Central Africa
	130 (200)	12.89 (12.89)	20.31 (20.31)	2.24 (3.44)	NW-Africa	Central Africa
	130 (200)	63.16 (−63.16)	−55.91 (124.09)	−0.98 (1.5)	NE-Africa	Central Africa
Torsvik et al. (2009)	130 (131.7)	50.00 (50.00)	−32.5 (−32.5)	54.37 (55.08)	Amazonia	S-Africa
	130 (131.7)	47.5 (47.5)	−33.3 (−33.3)	55.28 (56.00)	Paraná	S-Africa
	130 (131.7)	47.5 (47.5)	−33.3 (−33.3)	56.26 (57.00)	Colorado	S-Africa
	130 (131.7)	47.5 (47.5)	−33.3 (−33.3)	56.26 (57.00)	Patagonia	S-Africa
	130 (131.7)	33.65 (33.65)	26.02 (26.02)	2.31 (2.34)	NW-Africa	S-Africa
	130 (131.7)	40.50 (40.50)	−61.4 (−61.4)	−0.69 (−0.7)	NE-Africa	S-Africa
	–	–	–	–	Lake Victoria	S-Africa
	–	–	–	–	Somalia	S-Africa
Moulin et al. (2010)	130 (125)	53.42 (54.27)	−34.83 (−34.98)	51.73 (50.43)	Guyana	S-Africa (W-Africa)
	130 (125)	54.51 (55.4)	−36.10 (−36.31)	51.24 (49.95)	NE-Brazil	S-Africa (W-Africa)
	130 (125)	57.21 (57.21)	−38.40 (−38.71)	50.00 (48.76)	Tucano	S-Africa (W-Africa)
	130 (125)	52.82 (53.65)	−35.27 (−35.44)	52.31 (51)	São Francisco	S-Africa (W-Africa)
	130	51.34 (52.11)	−34.50 (−34.64)	54.32 (52.99)	Santos	S-Africa (W-Africa)
	130	51.95 (52.73)	−34.98 (−35.12)	54.95 (53.63)	Rio de la Plata	S-Africa (W-Africa)
	130	51.89 (52.67)	−35.19 (−35.34)	54.61 (53.29)	Argentina	S-Africa (W-Africa)
	130	51.89 (52.67)	−35.19 (−35.34)	54.61 (53.29)	Salado	S-Africa (W-Africa)
	130	51.89 (52.67)	−35.19 (−35.34)	54.61 (53.29)	Patagonia	S-Africa (W-Africa)
	130	27 (27)	−18 (−18)	1.5 (−1.5)	W-Africa (S-Africa)	S-Africa (W-Africa)
	130	27 (27)	−18 (−18)	−0.86 (−2.36)	Nubia	S-Africa (W-Africa)
	130	−7.50 (13.22)	26.84 (1.85)	−1.10 (−2.31)	Benue	S-Africa (W-Africa)
Seton et al. (2012)	130 (131.7)	50.136 (50.00)	−32.836 (−32.5)	54.855 (55.08)	Amazonia	S-Africa
	130 (131.7)	48.469 (47.5)	−33.364 (−33.3)	55.449 (56.00)	Paraná	S-Africa
	130 (131.7)	48.458 (47.5)	−33.364 (−33.3)	56.109 (57.00)	Colorado	S-Africa
	130 (131.7)	48.458 (47.5)	−33.364 (−33.3)	56.109 (57.00)	Patagonia	S-Africa
	130 (131.7)	33.65 (33.65)	26.02 (26.02)	2.00 (2.34)	NW-Africa	S-Africa
	130 (131.7)	40.50 (40.50)	−61.40 (−61.4)	−0.70 (−0.7)	NE-Africa	S-Africa
	130 (131.7)	15.0 (15.0)	37.2 (37.2)	−18.21 (−18.21)	Danakil	S-Africa
Heine et al. (2013)	130	48.94	−32.54	54.80	South American platform	S-Africa
	130	48.8	−32.49	54.76	Borborema Province Block	S-Africa
	130	47.59	−32.4	54.91	Salado	S-Africa
	130	47.59	−32.4	54.91	Pampean Terrane	S-Africa
	130	46.137	−32.29	54.97	Patagonia	S-Africa
	130	15.71	10.98	2.59	NW-Africa	S-Africa
	130 (140)	−0.13 (−0.13)	39.91 (39.91)	0.9 (1.35)	NE-Africa	S-Africa
	130	10.84	13.70	1.73	Jos	S-Africa
	130 (140)	8.25 (8.25)	6.95 (6.95)	−1.19 (−1.79)	Adamaoua (Benue)	S-Africa
	130	5.59	9.46	−7.11	Oban	S-Africa
	130	8.73	37.38	0.87	Bongor	S-Africa
Reeves et al. (2016)	130 (182.7)	42.943	331.055	58.637	South America	Congo Craton
	130 (182.7)	−2.346	17.824	7.049	NW-Africa	Congo Craton
	130 (182.7)	−2.346	17.824	7.049	Hoggar	Congo Craton
	130 (182.7)	−2.346	17.824	7.049	Niger	Congo Craton
	130 (182.7)	−10.530	35.310	3.790	NE-Africa	Congo Craton
	130 (182.7)	−15.089	33.640	3.329	Ethiopia	Congo Craton
	130 (182.7)	−3.660	29.900	3.000	Sudd Block	Congo Craton
	130 (182.7)	−4.179	33.790	7.569	Somalia	Congo Craton
	130 (182.7)	6.550	12.280	30.00	Hawal massif	Congo Craton
	130 (182.7)	–	–	–	Cameroon	Congo Craton
	130 (182.7)	–	–	–	NW Congo	Congo Craton
	130 (182.7)	–	–	–	Angola	Congo Craton
	130 (182.7)	–	–	–	NE Zambia	Congo Craton
	130 (182.7)	–	–	–	Zimbabwe	Congo Craton
	130 (182.7)	−4.000	210.000	2.000	Tanzania West	Congo Craton

(continued on next page)

Table 1 (*continued*)

Model	Age (Ma)	Latitude	Longitude	Angle of rotation	Moving plate	Fixed plate
	130 (182.7)	−37.672	210.701	0.654	Tanzania East	Congo Craton
	130 (182.7)	−36.000	345.000	0.500	Northern Mozambique	Congo Craton
	130 (182.7)	−14.060	7.620	0.20	Southern Kalahari	Congo Craton
	130 (182.7)	−23.314	333.567	13.080	Limpopia	Congo Craton
	130 (182.7)	−47.000	15.400	3.500	Beira High	Congo Craton
Richetti et al. (2018)	130 (140)	50.253 (50.992)	−33.987 (−34.121)	54.326 (52.985)	Amazonia	S-Africa (W-Africa)
	130 (140)	50.202 (50.940)	−34.113 (−34.252)	54.416 (53.075)	Borborema	S-Africa (W-Africa)
	130 (140)	52.373 (53.191)	−35.813 (−36.009)	52.944 (51.632)	Tucano	S-Africa (W-Africa)
	130 (140)	50.185 (50.922)	−34.067 (−34.204)	54.399 (53.057)	São Francisco	S-Africa (W-Africa)
	130 (140)	48.109 (48.788)	−33.579 (−33.724)	54.991 (53.628)	Paraná	S-Africa (W-Africa)
	130 (140)	47.52 (48.193)	−33.918 (−34.083)	55.104 (53.737)	Rio de la Plata	S-Africa (W-Africa)
	130 (140)	48.668 (49.366)	−34.385 (−34.552)	54.884 (53.529)	Pampean	S-Africa (W-Africa)
	130 (140)	51.133 (51.889)	−35.347 (−35.509)	55.269 (53.942)	Patagonia	S-Africa (W-Africa)
	130	27 (27)	−18 (−18)	1.5 (−1.5)	W-Africa (S-Africa)	S-Africa (W-Africa)
	130	27 (27)	−18 (−18)	−0.86 (−2.36)	Nubia	S-Africa (W-Africa)
	130	−7.50 (13.22)	26.84 (1.85)	−1.10 (−2.31)	Benue	S-Africa (W-Africa)
Müller et al. (2019)	130	49.9665	−32.5721	54.591	South America Craton	S-Africa
	130	49.9665	−32.5721	54.591	Paraná Basin	S-Africa
	130	42.0468	−34.189	60.199	Romeral-Colombia	S-Africa
	130	42.0468	−34.189	60.199	Maracaibo-Venezuela	S-Africa
	130	47.869	−32.3474	54.7371	Salado	S-Africa
	130	47.869	−32.3474	54.7371	Pampean Terrane	S-Africa
	130	46.8141	−32.2251	54.8476	North Patagonian Massif	S-Africa
	130	46.1927	−32.2665	54.7969	Deseado Massif Block	S-Africa
	130	17.9741	16.1945	2.45325	NW-Africa	S-Africa
	130	4	34	0.92	NE-Africa	S-Africa
	130	−48.85	17.57	1.01	Somalia	S-Africa
	130	19	42	−7.7	Danakil	S-Africa
	130	17.9741	16.1945	2.45325	Atlas	S-Africa
	130	35.9613	−2.60442	32.0077	Kabylie	S-Africa
	130	–	–	–	Lake Victoria	S-Africa
	130	–	–	–	North Mozambique	S-Africa

Northwestern and Northeastern Africa blocks. There is also intraplate overlap in the Somalia and Central Africa boundaries. As for South America, this model implies 30 km strike-slip movements between Paraná and Brazilian Craton as well as between Paraná and Salado blocks. Their fit shows gaps in the austral segment and overlaps for the central and equatorial segments of the South Atlantic.

Based on the fit of fracture zones and other geometrical constraints, Eagles (2007) proposed a reconstruction of the continental margins at the time of their breakup. The author suggests that previous rotations do not accurately describe seafloor spreading processes that immediately follow the breakup. Although the author assumed intracontinental deformation, he argues that the opening occurred within a two-plate system and his work only depict rotation poles of a single South American plate with respect to Africa. This precludes our reproduction of the model in terms of intraplate deformation but does not prevent us from discussing it. Supporting previous diachronous hypothesis, Eagles (2007) model requires a propagation from south to north of seafloor spreading that lasted ca. 40 Myr. This means that deformation must have been accommodated in the South American and/or African plates which is in accordance with recent models.

Torsvik et al. (2009) presented a revised model for the South Atlantic (Figs. 9i, 10i) based on Aptian salt accumulation, their interpretation of continent-ocean boundary and magmatic activities manifested as LIPs and SDRs. The authors assumed intraplate deformation in both South America and Africa plates and divided the first into four blocks: Amazonia, Paraná, Colorado and Patagonia; and the latter into five blocks: Northwest Africa, Northeast Africa, Somalia, Lake Victoria and South Africa. These divisions follow Nürnberg and Müller (1991) and Guiraud and Maurin (1992) proposals. Although Somalia and Lake Victoria blocks are shown in their reconstruction, the authors did not consider them fully active during the opening process. Torsvik et al. (2009) model presents 130 km intraplate overlaps in Africa near the Benue Trough. There are also intraplate overlaps in South America between Paraná, Colorado and Amazonia blocks. As for the margins, their reconstruction fits the continent-ocean boundaries in the austral segment without major misfits. In the central and equatorial segment, there are only overlaps.

An evolution of the Equatorial and South Atlantic oceans was proposed by Moulin et al. (2010) based on their compilation of data and interpretation of magnetic anomalies, seafloor isochrons, fracture zones, flow lines, homologous structures and radiometric dating of igneous rocks. Their model (Figs. 9j, 10j) corroborates the hypothesis of a northward propagation proposed by Eagles (2007). Assuming intraplate deformation, they divided the African plate into three main blocks following Guiraud and Maurin (1992): West, Nubian and Austral Africa with the additional Benue microplate and South America into nine blocks: Guyana, Northeast Brazil, Tucano, São Francisco, Santos, Río de la Plata, Argentina, Salado and Patagonia. Moulin et al. (2010) adjusted the Guinea and Demerara plateaus in a way that no further movement could be applied to this area and defined an incompressible zone in the Equatorial Atlantic. Their reconstruction shows intraplate overlaps between the African blocks and a small intraplate gap between the Guyana and Santos block in South America. There are also gaps along the margins in the austral segment of the South Atlantic and mostly overlaps in the central and equatorial segments.

Seton et al. (2012) proposed a reconstruction model built within a hierarchical plate circuit framework linked to a hybrid absolute reference frame that includes hotspots and a true polar wander corrected paleomagnetic-based model. Although their model is presented on a global scale, we will only address the South Atlantic continental and ocean floor reconstruction (Figs. 9k, 10k). The authors followed Torsvik et al. (2009) model and subdivided South America into eight blocks but only accounted for movements in Amazonia, Paraná, Colorado and Patagonia; while Africa was divided into twelve blocks but only Northwest Africa, Northeast Africa, South Africa and Danakil blocks are active during this time. As their rotation poles are also very close to those of Torsvik et al. (2009), their reconstruction presents similar aspects presented in that work.

Heine et al. (2013) compiled data from intraplate rifts in Africa and South America and proposed a plate kinematic model for the pre-

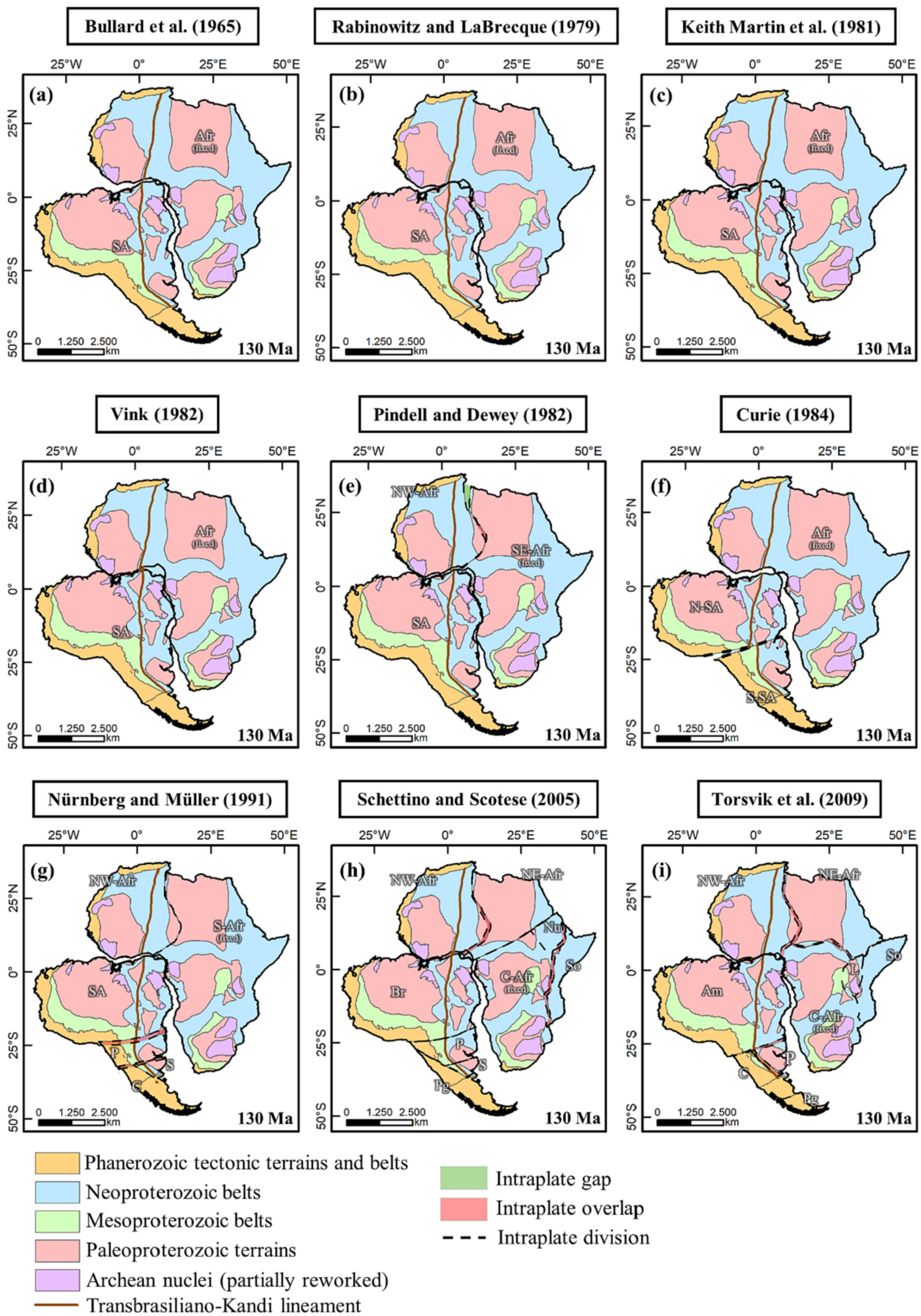

Fig. 9. Plate reconstruction of major geological units of each analyzed model. (a) Bullard et al. (1965) reconstruction at 130 Ma. (b) Rabinowitz and LaBrecque (1979) reconstruction at 130 Ma. (c) Keith Martin et al. (1981) reconstruction at 130 Ma. (d) Vink (1982) reconstruction at 130 Ma. (e) Pindell and Dewey (1982) reconstruction at 130 Ma. (f) Curie (1984) reconstruction at 130 Ma. (g) Nürnberg and Müller (1991) reconstruction at 130 Ma. (h) Schettino and Scotese (2005) reconstruction at 130 Ma. (i) Torsvik et al. (2009) reconstruction at 130 Ma. (j) Moulin et al. (2010) reconstruction at 130 Ma. (k) Seton et al. (2012) reconstruction at 130 Ma. (l) Heine et al. (2013) reconstruction at 130 Ma. (m) Reeves et al. (2016) reconstruction at 182,7 Ma *The same rotation poles provided by Reeves et al.

(2006) at 182,7 were used to depict the configuration at 130 Ma. (n) Richetti et al. (2018) reconstruction at 140 Ma. **The same rotation poles provided by Richetti et al. (2018) at 140 Ma were used to depict configuration at 130 Ma. (o) Müller et al. (2019) reconstruction at 130 Ma. Finite rotations used in each reconstruction are in Table 1. Abbreviations: A – Adamaoua; Afr – Africa; Am – Amazonia; Ar – Argentina; At – Atlas; B – Benue; Br – Brazilian Craton; BP – Borborema Province; C – Colorado; C-Afr – Central Africa; Cg – Congo Craton; De – Deseado Massif Block; E – Ethiopia; Guy – Guyana; J – Jos; K – Southern Kalahari; Kb – Kabylie; L – Lake Victoria; Ma – Maracaibo; Mo – Northern Mozambique; N-SA – Northern South America; NE – Northeast Brazil; NE-Afr – Northeast Africa; NW-Afr – Northwest Africa; Nu – Nubia; O – Oban; P – Paraná; Pg – Patagonia; PT – Pampean Terrane; R – Rio de la Plata; Ro – Romeral; S – Salado; SA – South America; S-SA – Southern South America; Sa – Santos; S-Afr – South Africa; SF – São Francisco; So – Somalia; T – Tucano; W-Afr – West Africa.

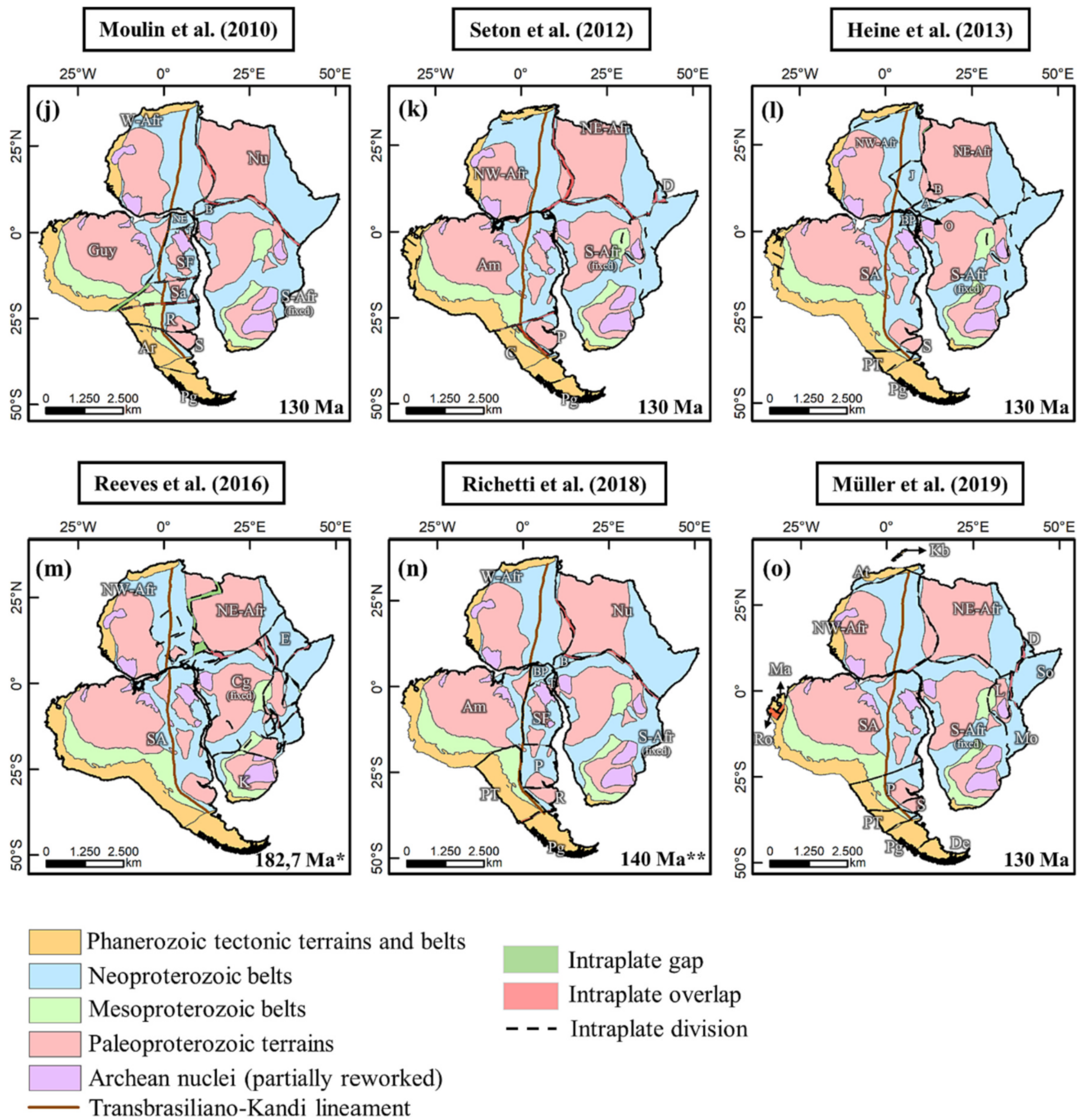

Fig. 9. (*continued*).

breakup evolution of the South Atlantic (Figs. 9l, 10l). Their work presented a multi-direction, multi-velocity extension history for the rift process that exerted primary control on the evolution of the conjugate passive margins systems. The authors quantitatively accounted for crustal deformation in these rift systems and introduced the concept of landward limit of oceanic crust (LaLOC), previously discussed. They also defined four major plate boundary zones and extensional domains namely the West African (WARS), Central African (CARS), South Atlantic (SARS) and Equatorial Atlantic (EqRS) Rift Systems. Therefore, their model focuses on the following continental lithospheric subplates for South America: South American Platform, Northeast Brazilian Borborema Province block, Salado, Pampean Terrane and Patagonia; and Africa: Northwest Africa, Northeast Africa, Southern Africa, Jos and Adamaoua (Benue), Oban Highlands and Bongor microplates. Regarding their fit, Heine et al. (2013) model does not present significant intraplate gaps or overlaps. On the margins, their model shows gaps in the austral segment and overlaps in the central and equatorial segments of the South Atlantic.

The model proposed by Pérez-Diaz and Eagles (2014) is based on seafloor spreading data such as the distributions and shapes of fracture zones and seafloor isochrons to describe the South Atlantic evolution. Their modeling procedure consisted of constraining isochron data to fit with their conjugates. Their work expanded Eagles (2007) opening model and corroborated the hypothesis of diachronous breakup in which intracontinental deformation can be interpreted as a response to stress accommodation associated with the northwards propagating rift.

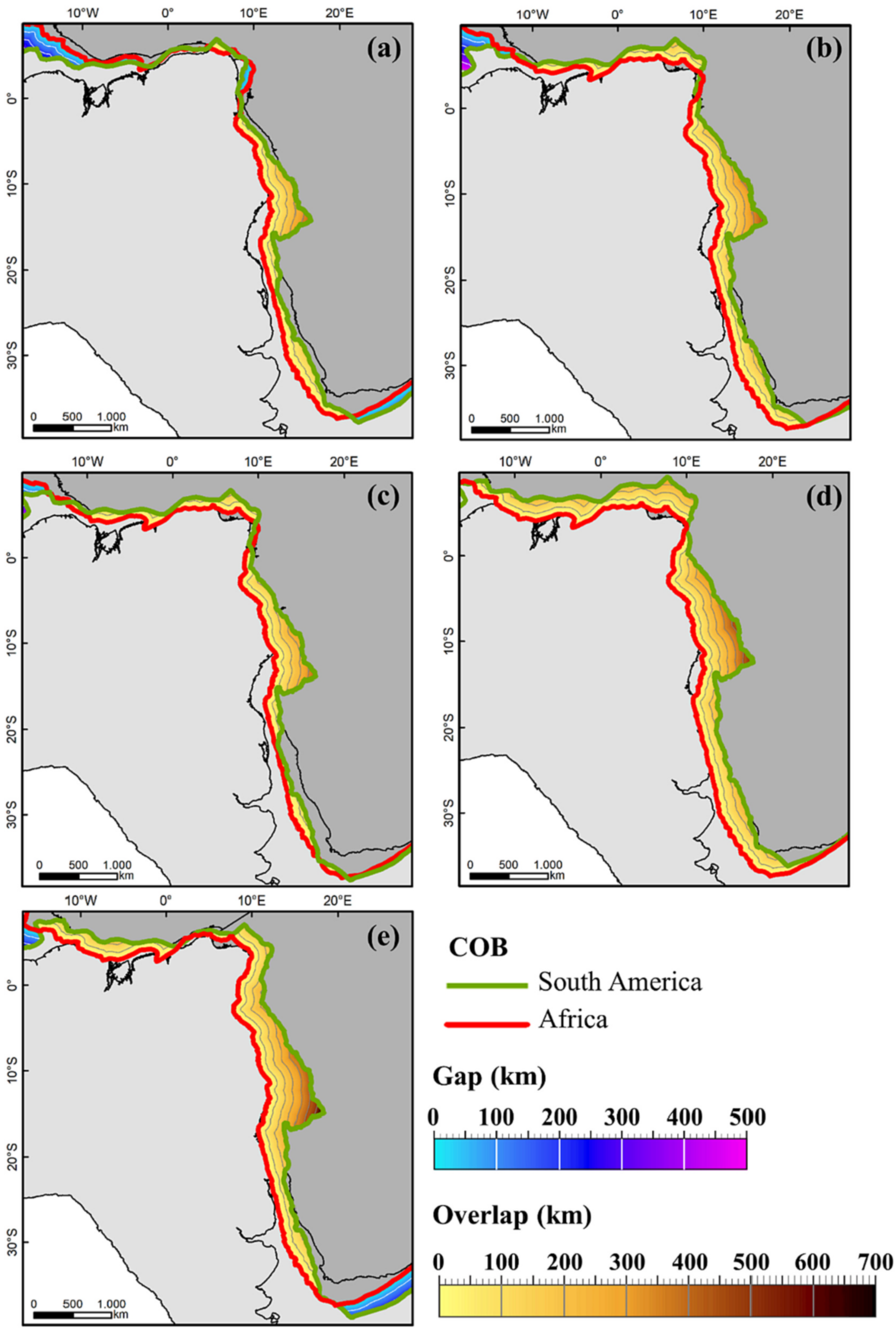

Fig. 10. Margin reconstruction of each analyzed model, in which continent-ocean boundary according to Heine et al. (2013) was rotated using each model parameters. Overlaps between these boundaries are in yellow/brown color grade and gaps in blue/purple. (a) Bullard et al. (1965) reconstruction at 130 Ma. (b) Rabinowitz and LaBrecque (1979) reconstruction at 130 Ma. (c) Keith Martin et al. (1981) reconstruction at 130 Ma. (d) Vink (1982) reconstruction at 130 Ma. (e) Pindell and Dewey (1982) reconstruction at 130 Ma. (f) Curie (1984) reconstruction at 130 Ma. (g) Nürnberg and Müller (1991) reconstruction at 130 Ma. (h) Schettino and Scotese (2005) reconstruction at 130 Ma. (i) Torsvik et al. (2009) reconstruction at 130 Ma. (j) Moulin et al. (2010) reconstruction at 130 Ma. (k) Seton et al. (2012) reconstruction at 130 Ma. (l) Heine et al. (2013) reconstruction at 130 Ma. (m) Reeves et al. (2016) reconstruction at 182,7 Ma. The same rotation poles provided by Reeves et al. (2006) at 182,7 were used to depict the configuration at 130 Ma. (n) Richetti et al. (2018) reconstruction at 140 Ma. The same rotation poles provided by Richetti et al. (2018) at 140 Ma were used to depict configuration at 130 Ma. (o) Müller et al. (2019) reconstruction at 130 Ma. Finite rotations used in each reconstruction are in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

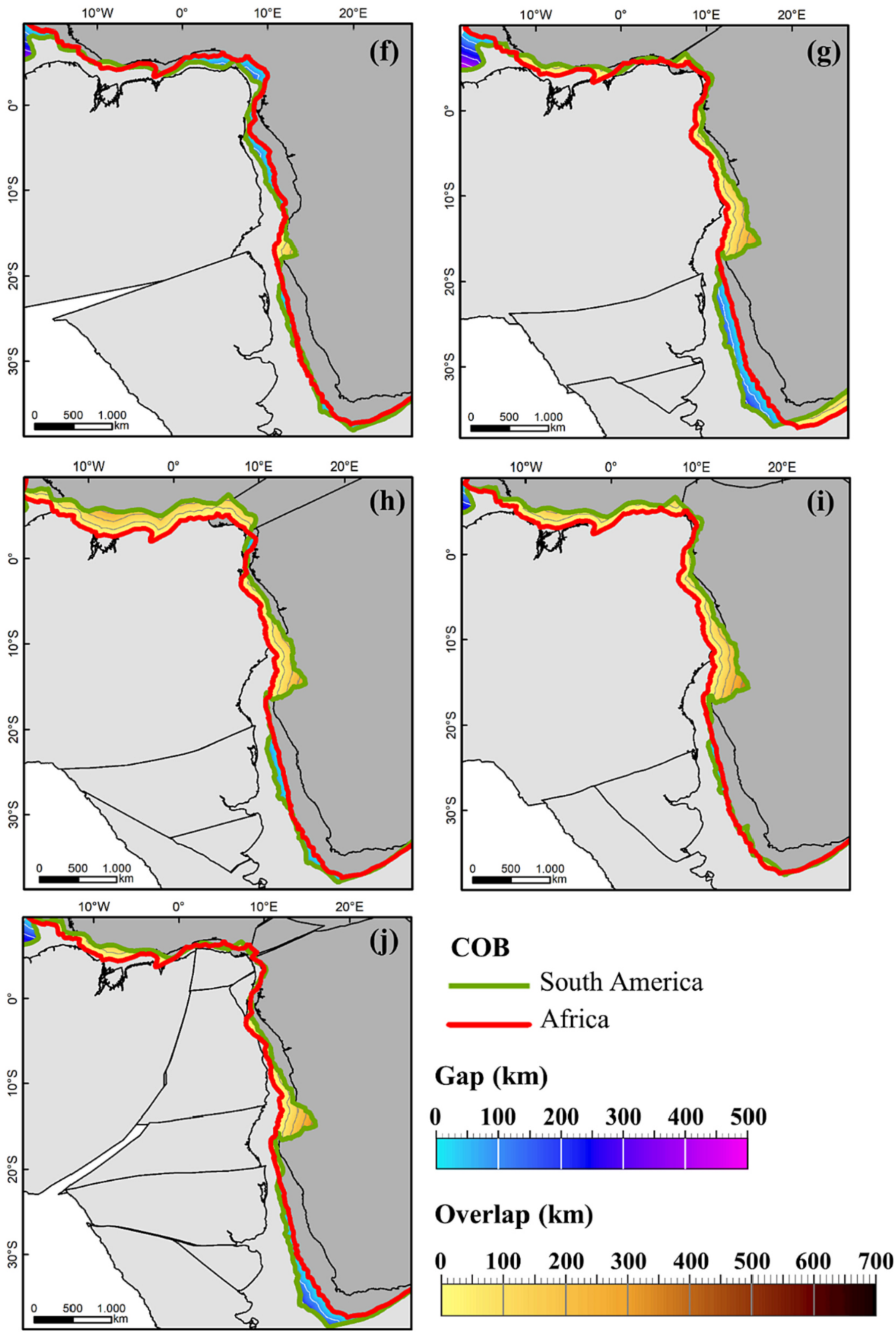

Fig. 10. (*continued*).

In this context, the authors proposed four accommodation zones in South America: Solimões-Amazon-Marajó basins, Recôncavo-Tucano-Jatobá basins, Salado-General Levalle basins and Colorado basin-Machín Trough; and four in Africa: Iullemeden rift, Termit-Bongor rift, Termit-Northern Benue rift and Central African-Muglad-Anza rift. Even though the authors present a full-fit reconstruction using their rotation to compare with Heine et al., (2013) model, they do not include these parameters on their work. In their comparison, Pérez-Diaz and Eagles (2014) concluded that their deformation zones account for 42–67% of the extension of the continental margins and the remaining 33–58% represent discrepant extensional strain.

Reeves et al. (2016) presented a plate tectonic model for the breakup

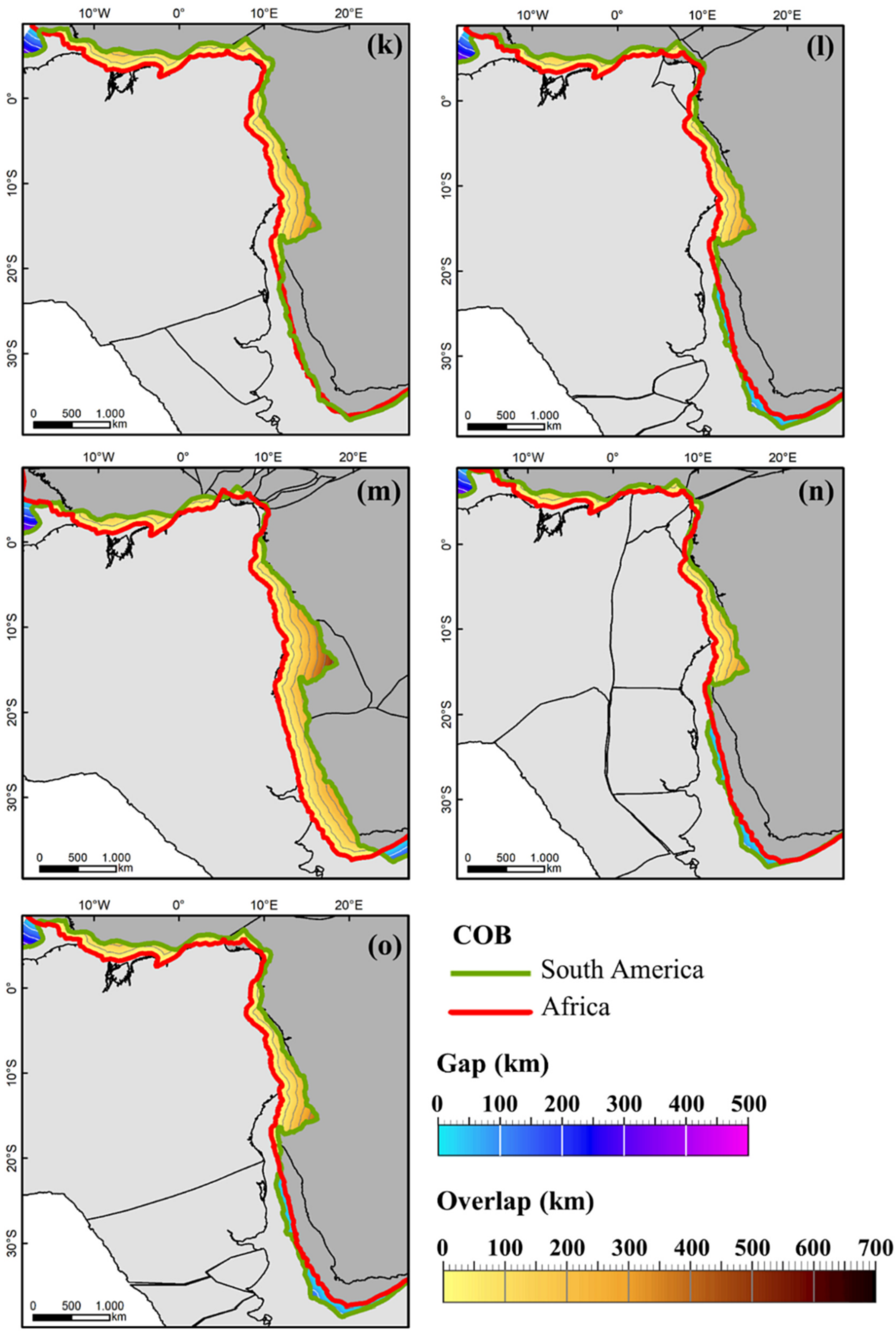

Fig. 10. (*continued*).

and dispersal of East and West Gondwana focusing on the formation of the Indian Ocean. We will only examine the West Gondwana plates in this review (Figs. 9m, 10m). In their work, the authors used ocean-floor fracture zone data and a tight assembly of Precambrian fragments of Gondwana constructed from geophysical and geological data. They proposed several blocks for Africa but considered South America as a single rigid plate. Their division of the African plate consisted of the Congo Craton, Northwest Africa, Hoggar, Niger, Northeast Africa, Ethiopia, Sudd, Somalia, Hawal massif, Tanzania West, Tanzania East, Northern Mozambique, Southern Kalahari, Limpopia and Beira High, with Cameroon, NW-Congo, Angola, NE-Zambia and Zimbabwe fixed in relation to Congo Craton. This model resulted in intraplate gaps near the

Benue Trough and on the northern portion of Africa; while overlaps are evident between most of the blocks' boundaries. The margins also show mostly overlaps from the austral through the equatorial segments of the South Atlantic.

Richetti et al. (2018), based on their studies of the tectonic and geological inheritance of the South America continent, proposed a new subdivision to this plate. They suggested eight rigid blocks in which each boundary was defined according to lithospheric scale structures that produced intraplate deformation during and after the Cretaceous rift. The proposed blocks are: Amazonia, Borborema, Tucano, São Francisco, Paraná, Río de la Plata, Pampean and Patagonia. They tested their model against the published models of African subplates from Moulin et al. (2010), Seton et al. (2012) and Reeves et al. (2016) and concluded that the rotations and subplates proposed by Moulin et al. (2010) produced the best with their subdivision model. This is the configuration that we will analyze in our review (Figs. 9n, 10n). Evidently, it shows the same intraplate African misfits of those of Moulin et al. (2010). In South America, the intraplate misfits are overlaps between the Pampean and Patagonia blocks as well as between Paraná and Rio de la Plata blocks. As for the margins, there are gaps in the austral segment of the South Atlantic while the central and equatorial segments show overlaps.

Müller et al. (2016) proposed a revised global plate model with continuously closing boundaries extending Seton et al. (2012) and Heine et al. (2013) models. Their work combined plate tectonic, plate boundary topology and oceanic paleo-age grids to reconstruct plate reorganization since the Pangea breakup. Müller et al. (2016) model was further refined by Matthews et al. (2016) that proposed an evolutionary and kinematic model since the late Paleozoic and also by Müller et al. (2019). Müller et al. (2019) presented a global deforming plate motion model since the Triassic that captures the progressive extension of continental margins throughout the Pangean rifting process. In order to avoid unnecessary repetition, we will analyze and review only the Müller et al. (2019) model (Figs. 9o, 10o) as it was built upon these very recent models.

In the South Atlantic region, Müller et al. (2019) employed the rift basin architecture to derive quantitative estimates of extension direction and magnitude. Their estimation of plate deformation at 130 Ma for the South Atlantic margins resulted in a stretching factor of approximately 2 in the austral and central segments and of approximately 1.2 for the equatorial segment. In their reconstruction, the authors proposed a division of the South American plate into eight blocks: South America Craton, Romeral, Maracaibo, Paraná, Pampean Terrane, Salado, Patagonia and Deseado Massif. Africa is divided into ten blocks: Northwest Africa, Northeast Africa, Atlas, Tunisia, Kabylie, Danakil, Somalia, South Africa, Lake Victoria and Northern Mozambique, but the last two blocks were not active during this period. This model results in a few intraplate overlaps such as the Romeral and Maracaibo blocks in South America as well as Danakil and Somalia blocks in Africa. On the margins, it implies gaps for the austral segment of the South Atlantic and overlaps for the central and equatorial segments.

6. Discussion

As shown in Figs. 9 and 10, the locations and magnitudes of overlaps and gaps between these reproduced models are, in general, considerably different. However, the most striking similarities are the overlaps in the central segment of the South Atlantic, near the Campos/Kwanza and Santos/Benguela basins. A possible explanation for this hyper-extended crust in Campos and Kwanza basins is a rift migration mechanism (Araujo et al., 2023; Brune et al., 2014) that most likely would have equally affected the Santos and Benguela basins (Kukla et al., 2018). We refer to Moulin et al. (2012) investigation based in kinematic reconstructions for a detailed review of the consequences of horizontal movements in the Santos basin. Additionally, some authors have suggested that the Santos and Campos basin have been affected by synrift magmatism (Gordon et al., 2023; Karner et al., 2021; Kukla et al., 2018; Mohriak et al., 2008), that may have influenced the margin architecture, especially when interrelated with basement inheritance (Stanton et al., 2019).

The first model reproduced and analyzed in this work is the one of Bullard et al. (1965) depicted in Figs. 9a and 10a. As pointed out by Keith Martin et al. (1981), Bullard et al. (1965) model did not include the Falkland Plateau which results in a gap of approximately 80 km between the steep north slope of the Falkland Plateau and the equally steep continental margin off the southeastern coast of South Africa. This reconstruction implies a maximum 500 km extension near the Campos/Kwanza and Santos/Benguela basins. It also leads to a gap in the Equatorial Atlantic that, according to Sibuet and Mascle (1978), was occupied by part of Cuba and the western part of the Bahamas platform. Due to the rigidity of plates, the simultaneous adjustment of southern and northern segments of the South Atlantic is impossible to obtain.

Rabinowitz and LaBrecque (1979) and Keith Martin et al. (1981) models present mostly overlaps along the margins and show many similarities (Fig. 10b and c, respectively). Compared to Bullard et al., (1965) pre-rift reconstruction, both models have reduced the gap between the Falkland Plateau and Africa but this is only accomplished by having large amounts of overlap along the northern portion (Vink, 1982). These reconstructions imply a *ca.* 550–500 km maximum extension for the pre-salt basins off the coasts of Brazil and Africa. In the northern portion of the central segment, extension seems to be overestimated and is not in accordance with estimations for this region (Milani and Davison, 1988). As for the conjugate Guinea and Demerara plateaus, the models result in a compressive zone that is larger in Rabinowitz and LaBrecque (1979) reconstruction reaching almost 200 km. Although compressional episodes have been reported in this region (Basile et al., 2013; Benkhelil et al., 1995) attributed to a plate kinematic change in late Albian times, these structures are local and do not reflect the multi-rift history of these plateaus (Olyphant et al., 2017). It was noted by Keith Martin et al. (1981) that these models necessitated non-rigid behavior such as crustal stretching or second-order intraplate movements. For instance, the authors pointed out that their alignment of the West Gondwana Orogen (Ganade et al., 2014) would require an eastward relative displacement of about 200 km for the Dahomeyan Front which implies an intraplate deformation in northwestern Africa.

Vink (1982) model differs greatly from others as it assumes significant overlaps along the margins (Fig. 10d). On a closer inspection of this proposal, Martin (1984) shows that Vink's assumptions are not entirely correct and that it is not necessarily valid that the crustal stretching increases with the progressive propagation of a rift. Unternehr et al. (1988) notices that Vink's reconstruction implies a broadening between the margins from south to north which does not correspond with reality. Moulin et al. (2010) also argues that this model shows overlaps between the Benue Trough and northeast Brazil and in the central segment of the South Atlantic that are incompatible with the geological constraints for these regions.

The most significant problems in Pindell and Dewey (1982) reconstruction seems to be related to the intraplate deformation in Africa, the poor adjustments in the central and austral segment and the displacement of Transbrasiliano-Kandi lineament (Figs. 9e and 10e). This model does not satisfy the West and Central African rift tectonics (Fairhead, 1988; Guiraud and Maurin, 1992; Unternehr et al., 1988) and therefore does not succeed in producing a good pre-breakup fit taking into account geological and structural data from this region. The fit for the Falkland Plateau shows gaps larger than Bullard et al. (1965) model. Moreover, the maximum overlap implied by this reconstruction seems to be overestimated as it is the widest from all analyzed models.

In Curie's (1984) proposal, the problems with poor adjustments is undoubtedly related to the chosen intraplate division for South America (Fig. 9f). The model shows major misfits in the conjugate margins with significant gaps for the regions of Cretaceous basins and the lowest extension of all the analyzed models for the central segment (Fig. 10f). This is because the author added, without any field evidence, a transcontinental strike-slip movement across the Paraná Basin in continuation to the Walvis-São Paulo ridges (Chang et al., 1992). Likewise, Nürnberg and Müller (1991) reconstruction (Figs. 9g and 10g) misfits are mostly associated with their intraplate division for South America. This division was proposed based on the authors' assumption of combined movements for these regions. Although the central segment appears to be in accordance with the estimated extensions for this region (Brune et al., 2014; Milani and Davison, 1988), there are no reports in the literature of intraplate extension and 80 km strike-slip movements in central and southern South America. In the African counterpart, their model implies a 60 km rifting in the Benue Trough that is in accordance with Fairhead (1988) estimations. Even though the authors have pointed out that a gap between the Guinea and Demerara plateaus before Aptian times is unlikely, the model still leaves a 100 km gap between them. The 130 km offset of Transbrasiliano and Kandi lineaments is also an important misfit of this model. In the austral segment, the gap implied by this reconstruction can be solved with the complex framework for this region proposed by Ramos (2008) and Heine et al. (2013).

Schettino and Scotese (2005) proposed an intraplate division that mostly follows Nürnberg and Müller (1991), but the boundaries of Northeast and Central Africa and Patagonia blocks are not explained by the authors and do not seem to follow any geological constraints. Nevertheless, the model (Figs. 9h and 10h) shows a relatively good fit for the central segment and for the Guinea and Demerara plateaus. The extension in the Benue Trough is also in accordance with geological records (Fairhead, 1988). However, Transbrasiliano and Kandi lineaments are offset by 70 km and the 50 km gap in the Borborema Province lacks explanation. The large overlap between the São Luis and West African Precambrian shields is also an issue (Moulin et al., 2010).

Most of the problems in Torsvik et al. (2009) pre-rift configuration (Figs. 9i and 10i) are underlined by Aslanian and Moulin (2010) comments. We will highlight a few of them here and include others. First of all, the boundary of the Patagonia block is defined by the Gastre fault system which according to field mapping and structural analysis cannot be supported as being a large-scale, intracontinental structural element (von Gosen and Loske, 2004). Also, Torsvik et al. (2009) Aptian salt extent is not entirely correct as it does not include the evidence of salt in Sergipe-Alagoas basin (Mohriak and Rosendahl, 2003). We argue that this could potentially change Torsvik et al. (2009) model as it was built upon the Aptian salt basins correlations. Aslanian and Moulin et al. (2010) pointed out the lack of coherence in the deformation of Salado and Colorado basin which plays an important role in the austral segment. Another problem seems to be the intraplate extension in the Benue Trough area which is larger than the amount estimated by previous authors (Fairhead, 1988; Unternehr et al., 1988). These issues are also observed in Seton et al. (2012) reconstruction model (Figs. 9k and 10k), seeing that it follows Torsvik et al. (2009) proposition, presenting similar intraplate subdivisions and rotation poles.

Moulin et al. (2010) reconstruction (Figs. 9j and 10j) implies an incompressible zone in the Equatorial Atlantic, which means that no further movement has occurred in this area. This seems to be the case only during the early phases of rifting between the Guinea and Demerara plateaus where mainly transform motion occurred. However, simple-shear extension followed by compressional and tensional phases were reported for this region (Benkhelil et al., 1995; Olyphant et al., 2017). This model was the first to recognize the importance of Transbrasiliano lineament as an intraplate boundary, but the authors have incorrectly traced its location, bending it to northern Chile. This delimitation resulted in an intraplate gap between Guyana and Santos blocks. Another three limits do not follow geological evidence: the boundaries between Río de la Plata and Santos, between Santos and São Francisco and between Argentina and Patagonia. The first is defined as a dextral shear zone but no direct evidence of intraplate deformation is described and the second appears to be chosen arbitrarily parallel to the Ponta Grossa dike swarm (Richetti et al., 2018). The latter follows the Gastre fault system that, as previously discussed, does not show any field evidence regarding intraplate deformation (von Gosen and Loske, 2004). In the African counterpart, intraplate deformation is in accordance with geological and geophysical studies in the Central and West Africa rift systems (Fairhead, 1988; Guiraud and Maurin, 1992), but a small gap on the boundary of Benue microplate is inexplicable. The authors seem to have included part of this gap in the incompressible zone, but then again, its geological significance is not clear.

The reconstruction model proposed by Heine et al. (2013) is robust and well-constrained (Figs. 9l and 10l). The authors have achieved a tight-fit reconstruction based only on intraplate rifts, that is, they do not consider complex intracontinental shear zones. Therefore, it is reasonable to hypothesize that this model could be refined by including, for instance, Precambrian shear zones with evidence of reactivation. By considering the South American platform a single block, this model requires a contemporaneous rift in the central segment of the South Atlantic. However, as the authors have noticed, stratigraphic data suggests different onset of the *syn*-rift phase in the marginal basins (Chaboureau et al., 2012; Mohriak et al., 2002 and references therein). Although Heine et al. (2013) did not consider the Transbrasiliano lineament an intraplate boundary, they do not refute evidence of reactivation of this feature during the opening of the South Atlantic (Fairhead and Maus, 2003; Pérez-Gussinyé et al., 2007; Richetti et al., 2018 and references therein).

Reeves et al. (2016) proposal lacks subdivision for South American plate, but assumes several blocks in Africa which correspond to Precambrian fragments (Figs. 9m and 10m). This results in several problems on the margins previously discussed, such as an overestimation of extension in the central segment, the assumption of a coeval syn-rift phase for marginal basins and gaps between the Falkland plateau and South Africa. It also does not correspond with the West and Central African rift tectonics (Fairhead, 1988; Guiraud and Maurin, 1992; Unternehr et al., 1988).

Richetti et al. (2018) proposed subdivision of South America is here analyzed against Moulin et al. (2010) African blocks (Figs. 9n and 10n). Overall, the authors achieve a tight-fit reconstruction constrained by crustal discontinuities that accommodated stress within the continents, especially in the South American plate. The intraplate misfits on the African plate are the same discussed in the Moulin et al. (2010) review. Intraplate overlaps on the South American counterpart are evident between the proposed blocks and can be justified by geological evidence. For instance, overlaps on Tucano block boundary can be explained by extension in the Recôncavo-Tucano-Jatobá basins (Milani and Davison, 1988) while the overlap between the Pampean and Amazonia blocks is consistent with a possible accommodation in the Tucavaca aulacogen (Ramos et al., 2010). The authors suggest solving the overlap between Paraná and São Francisco blocks by extension in the Ponta Grossa dyke swarm region. They also argue that overlaps in Rio de la Plata block can be explained by extension in Salado and Colorado basins. Regarding the margins, this model shows overlaps in the central and equatorial segment, probably related to extension on the marginal Cretaceous basins as previously discussed and a gap in the austral segment that can be explained by the evolution proposed by Ramos (2008) and Heine et al. (2013).

Müller et al. (2019) reconstruction model for the South Atlantic region (Figs. 9o and 10o) was built on previous models, including the one previously analyzed in this work of Heine et al. (2013). However, contrary to Heine's et al. model, the authors do not consider an intraplate division of the Borborema Province block. Therefore, extension in Recôncavo-Tucano-Jatobá basins is not accounted for. On the margins, their model shows similar features to previous models, which we have discussed in Heine et al. (2013) and Richetti et al. (2018) reviews. Intraplate misfits on the African plate are also similar to Torsvik et al. (2009), Seton et al. (2012) and Heine et al. (2013). In the South American plate, gaps in the Pampean Terrane and Patagonia boundaries can be explained by compressive deformation along the Patagonian

Andes (Flament et al., 2014). The overlaps of Romeral and Maracaibo blocks can be explained by reactivation of the Romeral fault system which has been active since the Triassic (Vinasco and Cordani, 2012).

All in all, each model presents its pros and cons, and their proposals have given valuable insights to advancing knowledge on West Gondwana breakup and pre-rift configuration. Nevertheless, models accounting for fully rigid plates have several limitations, so that a better fit is achieved by assuming intraplate deformation. Building a plate model with distributed deformation can help explain several geological and geophysical observations, and account for extensional and compressional processes that have evolved during Gondwana dispersal (*e.g.*, Heine et al., 2013; Moulin et al., 2010; Müller et al., 2019; Nürnberg and Müller, 1991; Pérez-Diaz and Eagles, 2014; Reeves et al., 2016; Richetti et al., 2018; Schettino and Scotese, 2005; Torsvik et al., 2009). Moreover, quantifying intraplate deformation has allowed modeling the time-dependent velocities and extension direction in the South Atlantic rift (*e.g.*, Heine et al., 2013), as well as estimating stretching factors and crustal thickness changes through time (*e.g.*, Müller et al., 2019). The definition of intraplate boundaries directly influences block rotation, and it is evident that such limits should be delineated based on geological and geophysical constraints. For that reason, most problems faced in reconstructions are related to the location, timing, and amount of deformation, due to the limited data on lithospheric extension products in the continental interiors. Improvements to such models will benefit from new, detailed thermochronology, structural and stratigraphic data, along with more detailed geophysical and geological regional datasets.

Another problem arises from the Cretaceous prolonged interval of stable polarity in the Earth's magnetic field, the Cretaceous Normal Superchron (CNS) that lasted from approximately 121 to 83 Ma (Cande and Kent, 1995; Granot et al., 2012). Since seafloor spreading started during this magnetic quiet zone, determining the exact timing of opening is challenging. Kinematic models are based on interpolation between the rotation parameters, in which movements are calculated to obtain the best fit of corresponding magnetic anomalies, fracture zone systems and conjugate structures (*e.g.*, Moulin et al., 2010; Nürnberg and Müller, 1991). However, in a pre-breakup configuration, oceanic magnetic anomalies or fracture zones are lacking, which makes the quantification of horizontal deformation more complicated. Several approaches have been proposed to overcome this situation, such as constraining rotation parameters with the seaward limit of the salt basins (Torsvik et al., 2009), quantifying rift infill, faulting and post-rift subsidence (Heine et al., 2013), or introducing nonmagnetic isochrons to fit small circle segments to picked fracture zones throughout the CNS (Pérez-Diaz and Eagles, 2014). Another solution seems to be the merger of local constraints with large-scale plate kinematic modeling, as proposed for the North Atlantic (Nirrengarten et al., 2018). More detailed research on the behavior of the geomagnetic field during the CNS may provide data to refine time markers (*e.g.*, Granot et al., 2012) and improve reconstruction models.

Finally, we point out that each segment of the South Atlantic has its temporal and spatial evolution that is characterized by: (i) higher magma budget in the austral segment (evidenced by the presence of seaward-dipping reflectors; Moulin et al., 2010; Stica et al., 2014); (ii) distribution of Aptian salt in the central segment (Epin et al., 2021; Kukla et al., 2018; Mohriak et al., 2008; Torsvik et al., 2009); and (iii) transform faulting and oblique motion that marks the evolution of the equatorial segment (Heine and Brune, 2014; Mohriak and Rosendahl, 2003; Nemčok et al., 2013). It has also shown that even within a segment, the margin architecture is controlled by several factors, including inheritance, magmatic activity and changes in the rift asymmetry (Epin et al., 2021 and references therein). Therefore, future reconstruction models can greatly benefit from more detailed distal margin studies, including new interpretations on seismic profiles.

7. Conclusion

Reconstruction depicting pre-rift configuration of South America and Africa have been made using various methods and constraints, such as isobaths (Bullard et al., 1965), by fitting marine gravity and magnetic anomalies and seafloor data (Lawver et al., 1998; Pérez-Diaz and Eagles, 2014; Rabinowitz and LaBrecque, 1979; Reeves et al., 2016), by matching tectonic features (Keith Martin et al., 1981; Richetti et al., 2018) or by using a combined continental and marine geophysical and geological database (Eagles, 2007; Heine et al., 2013; Matthews et al., 2016; Moulin et al., 2010; Müller et al., 2019, 2016; Nürnberg and Müller, 1991; Seton et al., 2012; Torsvik et al., 2009).

We presented here a review and reproduction of 15 published reconstruction models since Bullard et al. (1965) pioneering work. We have analyzed them based on compiled geological and geophysical data on a continental scale. We underline the importance of each model in the evolution of knowledge regarding the South Atlantic opening, hence, we do not diminish any proposed model.

Comparison of the reconstruction models at 130 Ma shows a few similarities between these proposals. In general, overlaps are more widespread than gaps. Most models imply overlaps in the Equatorial Atlantic, varying from *ca.* 100 to 200 km. Some authors have argued that a gap between the Guinea and Demerara plateaus before Aptian times is unlikely (*e.g.* Nürnberg and Müller, 1991). A common feature in all reproduced models is the maximum implemented overlap near the Campos/Kwanza and Santos/Benguela basins. Overlaps are also expected in the northern part of the central segment, which could possibly be explained by extension in the Recôncavo-Tucano-Jatobá basins (Milani and Davison, 1988). The austral segment marks the disparity between the reconstructions, where gaps and overlaps have been proposed. Fit differences result mostly from the assumed internal and/or external deformation. In the first case, stresses resulting from the breakup are mostly absorbed by intraplate deformation, usually on inherited structures that are reactivated. In the latter, it is the deformation dynamics of the margin that results in strain, with little to no contribution from intraplate structures.

Although plate reconstruction models depicting West Gondwana pre-rift configuration have increasingly become more detailed and robust, problems remain regarding the location of intraplate boundaries, in which inherited lithospheric discontinuities should not be overlooked. The lack of recent and open-access data for the African intraplate rifts also results in reconstruction uncertainties. Other issues are related to the timing and quantification of intraplate deformation in reactivated continental structures, the lack of oceanic magnetic anomalies due to the CNS, and the influence of magmatic additions on margin restoration. Future reconstruction models must rely on detailed structural, stratigraphic, geochronological, geophysical and geological datasets. Studies on the influence of previous Pangea breakup processes in the reactivation of inherited structures and the further refinement of continental intraplate boundaries may help understand the role of intraplate deformation in the evolution of South Atlantic opening.

CRediT authorship contribution statement

Juliana Fernandes Bonifacio: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Carlos Eduardo Ganade:** Conceptualization, Methodology, Writing – review & editing, Supervision, Resources, Funding acquisition. **Anderson Costa dos Santos:** Conceptualization, Methodology, Writing – review & editing. **Ricardo Ivan Ferreira da Trindade:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

Data availability

Data will be made available on request.

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