# South Atlantic Rift Segmentation from Demerara to Walvis: The Interplay between Strike Slip Deformation and Rifting*

**Renato M.D.de Matos[1], Ian Norton[2], Ana Krueger[3], and Katya Casey[4]**

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[1]Nandy Oil and Gas, Rio de Janeiro, RJ, Brazil
[2]Institute for Geophysics, The Universtiy of Texas at Austin, Austin, TX
[3]Independent Consultant, Houston, TX (akrueger@icloud.com)
[4]Actus Veritas Geoscience LLC, Houston, TX

## Abstract

In our multidisciplinary study we have used kinematic indicators to investigate lithospheric processes linked to tectonic plate separation during rift propagation along volcanic and nonvolcanic margins of the South Atlantic. The project covers the time from pre-rift to a fully established marine connection between the South and Central Atlantic. We define in space and time five Kinematic Stages and five main Structural Segments of the South Atlantic, based on deformation partitioning along the margin from Demerara/Guinea to Walvis Ridge/Rio Grande Rise.

## Introduction

New data and development of new concepts have dramatically changed our understanding of the evolution of passive continental margins, such as those surrounding the South Atlantic. Significant intracontinental deformation has been invoked by some authors to explain spatial misfits in pre-breakup plate configuration (Pérez-Días and Eagles, 2014, Heine at al., 2013, Moulin et al, 2010, among others). Some of the misfits were related to inconsistent breakup markers, but selection of reliable markers with minimal error bars is still a challenge. The difficalty of defining the best pre-breakup fit of the plates is also genetically linked to the time domain, where methodology-related age misfits challenge any kinematic modelling.

Rifting between South America and Africa started in the Late Jurassic - Early Cretaceous and eventually led to formation of the South Atlantic Ocean. Sea-floor spreading began in the Hauteruvian in the far south of the South Atlantic, with onset of spreading generally propagating northward, ultimately being fully developed in the equatorial South Atlantic in the late Albian/early Cenomanian. However, rifting was more complex with significant local variations in the timing of rift initiation, orientation of rift propagation, and resulting basin architecture. The timing of the events was controlled by the contrasting lithospheric stretching modes of each margin segment.

Deformation partitioning was controlled by spatial distribution of lithospheric keels and the roots of thick and stable Proterozoic cratons and their associated mobile belts. Figure 1 is a snapshot of west Gondwana at 145 Ma with main geological structures that influenced the lithospheric rupture process, and the distribution of pre-rift sediments and active rift axes at that time. The controling structural elements are the **TBL, TSL, TA, BHS** lineaments and the Precambrian cratons (Figure 1).

## The Proterozoic Heritage

Figure 1 illustrates the cratons (shaded), the mobile belts and shields (white) and the most important shear zones. The Brasiliano/Pan African tectonic event produced one of the main structures of West Gondwana: The 3000-km-long Trans-Saharan (**TSL**) lineament and its southward continuation: the Transbrasiliano Lineament (**TBL**, from NW Ceará, in Brazil, all the way to Argentina), another 3000-km-long shear zone. The Sobral fault in Brazil aligns perfectly with the Kandi fault in Africa. The **TSL** borders the West African Craton, with associated arc-related Neoproterozoic rocks, ophiolites and accretionary prisms (Kröner and Stern, 2004). The **TBL** separates the Amazon Craton (Amazonian or pre-Brasiliano domain) from the Brasiliano domain (Brito Neves at al., 2014), which was remobilized along metamorphic shear zones during the Pan-African–Brasiliano thermo-tectonic event (about 600 Ma, Caby, 1989). Linked with the **TBL** is what we refer to as the Borborema Horsetail Splay (**BHS**). This feature is defined by a complex framework of NNE-trending orogenic branching systems in Brazil, and it continues into Africa (Figure 1). Included in this zone is the Transversal Zone (**TZ**, Brito Neves at. Al, 2016, Matos,1998), which is part of the Borborema province. Also in this zone are the Patos (**LPT**) and Pernambuco (**LPE**) lineaments. The **LPT** has been recognized as a continental transform (Brito Neves et al, 2016). The **BHS** encompasses parts of the Nigerian and Borborema shields, associated with high-grade metamorphism and extensive lateral displacement of crustal blocks along oblique strike-slip faults, mostly right-lateral. This represents a large continent-scale lithospheric root, roughly east-west, orthogonal to any future northward rift propagation. For this reason, we are naming this feature the *Orthogonal Segment or* ***Orthogonal Zone*** (**OZ**).

## Kinematic Stages – Time and Space Partitioning

In the **Space domain**, five Structural Segments can be conveniently defined, based on their extensional deformation mode and the location of the major fracture zones clearly identifiable in the oceanic crust (Figure 2).

The Segments from north to south are:
1) **Dextral Equatorial Domain (Demerara to Charcot FZ),** characterized by dextral strike slip rifting followed by wrench tectonics, with the development of long offset transform margins and short oblique passive margins. Deformation partitioning was related to clockwise rotation of South America relative to Africa; this led to the development of distinct tectonic environments: Pure-Shear-Dominated Transtension (**PSDTt**), Wrench-Dominated Transtension (**WDTt**) and Wrench-Dominated Transpression (**WDTp**).
2) **Benue-Pernambuco Plateau Orthogonal Domain (Charcot to Kribi-Ascension FZs),** in which pure extension (**PE**) evolved into normal passive margins separating, mechanically, the right-lateral segments from the left-lateral. Spatially, this segment belongs to the Orthogonal Zone (**OZ** or the **BHS –** Borborema Horsetail Splay), which acted as a continental scale relay zone, preventing and postponing the link between the Equatorial and the

South Atlantic rift branches. Basins of segments 3, 4 and 5 make up the Sinistral domain of the Central Salt Basins (**CSB´s**). This domain encompasses the basins between Kribi and Florianópolis Fracture Zones.

3) **<u>The Northern Buffer Zone (Kribi to Bode Verde FZs)</u>,** developed under a sinistral Pure Shear-Dominated Transtension (**PSDTt**), that evolved into oblique passive margins;

4) **<u>The Central compartment (Bode Verde to St Helena FZs)</u>** in which, like segment 2, pure extension (**PE**) evolved into normal passive margins; and

5) **<u>The Southern – Aptian Buffer Zone (St. Helena to Rio Grande Walvis FZs)</u>,** similarly to segment 3, a sinistral Pure Shear-Dominated Transtension (**PSDTt**), that evolved into oblique passive margin.

Segments 3 and 5 have similar characteristics acting as kinematic "Buffer Zones". The term refers to a system of transform faults linked into a relay zone accommodating differential extension between the adjacent rift segments.

On the other hand, in **Time domain,** we use kinematic indicators as a simple criterion. Even though adjacent basins along the margin may have synchronous depositional sequences, important kinematic, environmental or tectonic changes may be hidden in the sedimentary record. Therefore, instead of using tectonic environmental boundaries, like pre-, syn-, and post-rift, we had chosen to recognize ***kinematic stages*** *which are* not defined in the stratigraphic record. The recognition of five kinematic stages was a result of sorting in time twenty Kinematic indicators--the basis for recognition of the time delays in the structural partitioning of the margins and the influence of Proterozoic heritage.

Figure 3 and 4 illustrate simplified stratigraphic charts of Brazilian and African basins, and the interpreted kinematic stages (S1 to S5). There are too many basins to be illustrated in a single figure. Figure 4 has a zoomed, simplified view of Figure 3 with explanation of the acronyms. Every stage has a time range. Their boundaries are characterized by remarkable kinematic changes across the transform fault systems with either development of new rift basins, exhibiting major spatial changes along the active rift axes or the abortion of previously developed rift axes.

The oldest rifts of the future site of the Equatorial and South Atlantic Margins seem to be triggered solely by the distribution and partitioning of intracontinental strain, because there are no major magmatic activities during the <u>Kinematic Stage 1</u>.

During the busy <u>Kinematic Stage 2</u>, rifts activity propagated southward, linking simultaneous rifting from North Gabon towards Santos-Namibia, synchronous with the Early Cretaceous South Atlantic Magmatic Province (**SAMP**), defined by the intrusion of transversal dike swarms (**PGA**, Ponta Grossa dike swarms in Figure 1) and continental flood basalts, active from about 135 to 114 Ma (Szatmari and Milani, 2016) at the time of the initial clockwise rotation of South America with respect to Africa. Fragmentation of the West African Craton is recorded in the Gurupi graben system. The initiation of the Cariri-Potiguar-West Africa rift orientation is contemporary with the eastward propagation of the West African rift system, opening the way towards the Cariri-Potiguar rift axis in Brazil, which is part of the **NBRS** (Northeast Brazilian Rift System of Matos, 1992).

During the early Aptian (<u>Kinematic Stage 3</u>), an intracontinental dextral strike-slip system developed at the Equatorial Atlantic, when the lithospheric limits between South America and Africa began to be delineated (Matos, 1999, 2000, and 2005).

Kinematic Stage 4 in late Aptian time is characterised by the lithospheric separation between Africa and South America. For the first time, rifting was taking place at the same time at the Equatorial and South Atlantic. Here we emphasize the "**Aptian Buffer zone**", a relay zone (Buffer Zone of Moulin et al., 2010), balancing mechanically hyper-extended terrains of the Santos-Namibia block, with the northern part of the CSB´s. However, the entire South Atlantic branch was anchored at the Orthogonal Zone (rift tip at the Pernambuco Lineament shear zone), which behaved as a large-scale transfer zone, hindering rift propagation. Therefore, there is a genetic connection between the Aptian Buffer Zone with the Orthogonal zone, and with the tectonic evolution that led to the huge pre-salt reserves. Later at this stage: As the Equatorial strike-slip system developed, and the Aptian Buffer zone became wider, intracontinental rifting started at the Orthogonal Zone. This new rift axis cut at high angle the BHS rock fabric, giving birth to the Pernambuco-Paraíba/Benue-Rio Muni (P-B-RM) rift axis (Matos et al., 2004, Matos, 2005).

During early Albian (kinematic Stage 05), a dextral transform plate boundary began to be developed in the Equatorial Atlantic, linking the Central and South Atlantic, until the lithosphere became critically thinned and sea-floor spreading started.

From early Aptian to late Albian, at least, a pure shear-dominated Orthogonal Domain balanced deformation between the Sinistral Equatorial Domain and the Dextral Central Salt Basins Domain. The Orthogonal Domain mechanically balanced contrasting lithospheric stretching stages between the Equatorial and the CSB´s, enabling the development of a second, **Albian buffer zone** at the northern tip of the CSB´s. This segment acted as another, younger relay zone, balancing extension south of the Orthogonal Domain. It is a good example of deep-water rifting in hyper-extended continental crust, simultaneous with sea-floor spreading basinward, documented by dated Albian-Cenomanian volcanics interbedded with marine rift sediments in the Sergipe-Alagoas basin (Caixeta et al. , 2014).

The Equatorial separation evolved into full sea-floor spreading during the Aptian-Cenomanian. The dynamic juxtaposition of continental crust against oceanic crust or spreading centers on the opposite side of a transform fault caused diachronous deformation, recorded in the sedimentary record as important unconformities, amplified or not by synchronous eustatic sea-level variations (Matos, 2005). Even though full continental separation was achieved in the late Albian, plate tectonic interactions and lithosphere dynamics still influenced the Equatorial basins during the Cenomanian (Figure 5).

## Concluding Remarks

An integrated interpretation, in the space-time domain, of the South Atlantic margin led to recognition of five Kinematic Stages and five Structural Segments (or groups of marginal basins), genetically linked with oceanic transform faults. The Orthogonal Domain separates a Dextral (Equatorial) domain from a Sinistral (Central Salt basins) domain, which is composed of three segments, including two diachronous buffer zones, with hyper-extended terrains. Lithospheric keels and the roots of thick and stable Proterozoic cratons and their associated mobile belts controlled the site of a large-scale relay zone (Orthogonal Segment) and the buffer zones, fragmenting, in time and space, the rupture of Gondwana.

Major differences arise from the distinct tectonic evolution of each margin segment, the result of a complex and dynamic lithospheric stretching process. At the Central Salt Basin segment, upper crustal inhomogeneities and synchronous magmatism had a very important role in the location and architecture of the basins. On the other hand, in the Orthogonal and Equatorial Segments, minor syn-rift magmatism and upper crustal rock fabrics had little influence on basin architecture. Lithospheric keels and how they became connected between each other during the fragmentation process seem to have been a key controlling factor in these two segments.

Hydrocarbon exploration has been most successful in the sinistral domains, and even more so in the hyper-extended, Aptian and Albian buffer zones.

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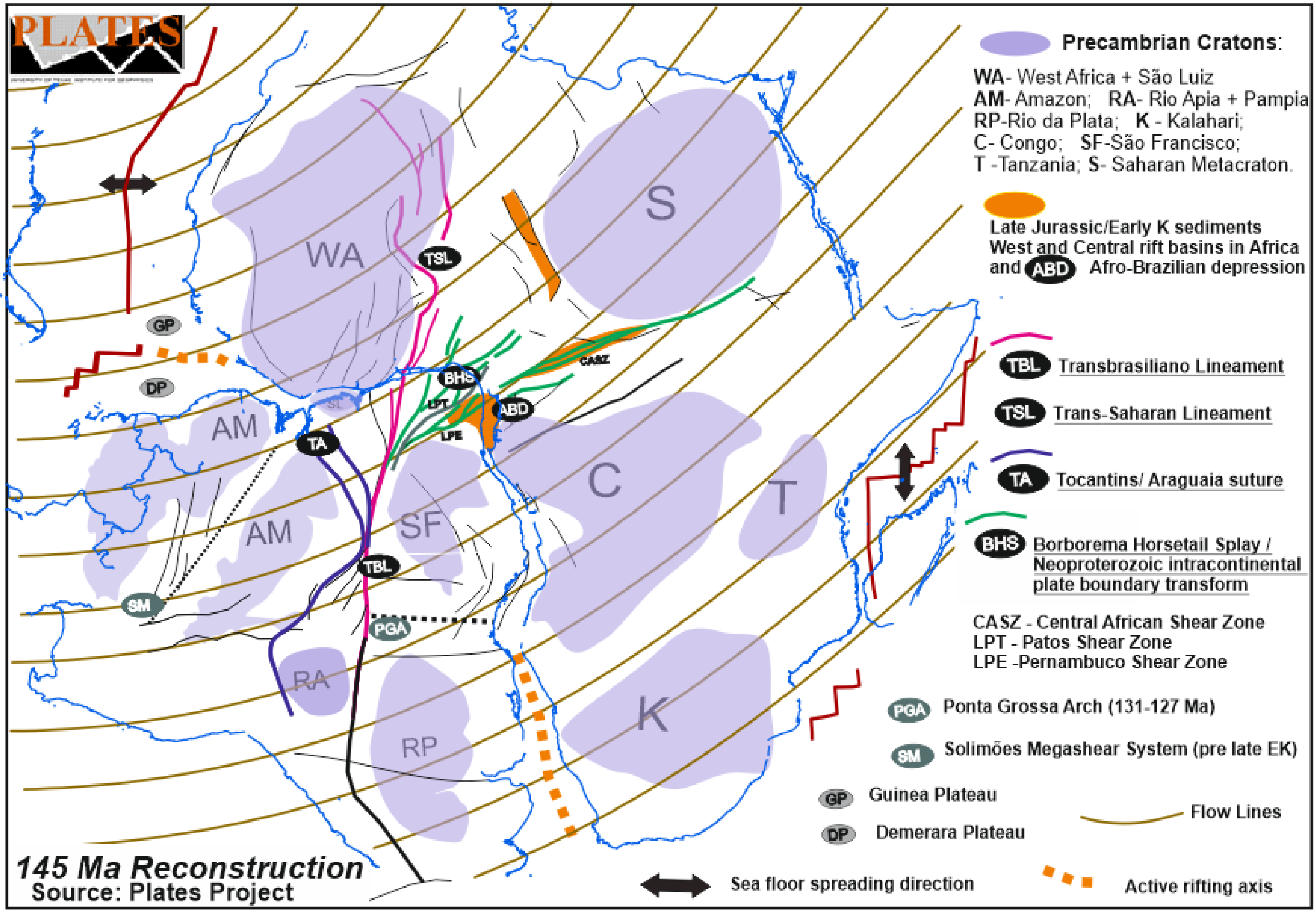


Figure 1. General tectono-structural map of the South Atlantic Ocean at 145 Ma, which summarizes the main geological structures that influenced the lithospheric rupture process, the distribution of Pre-rift sediments, and active rift axes at that time. Flow lines are small circles about the early motion Euler pole between Africa and South America and define direction of relative motion. The Orthogonal Zone (**OZ**) is a large continent-scale lithospheric root, roughly an east-west net of Proterozoic shear zones (**BHS** and parts of the Nigerian and Borborema shields).

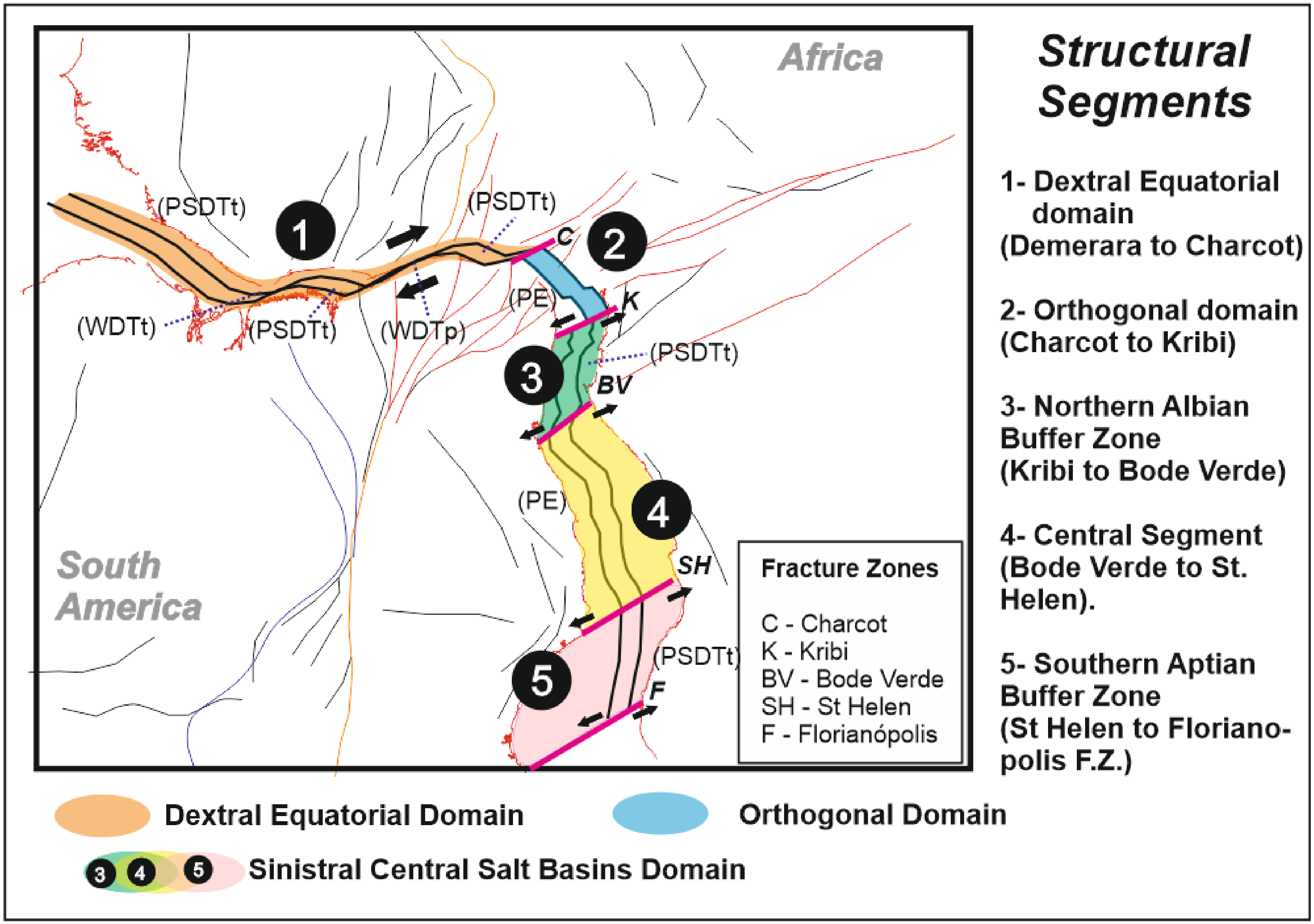


Figure 2. Main structural segments of the South Atlantic. A Dextral (Equatorial) domain and a Sinistral (Central Salt basins) domain are separated by the Orthogonal domain (Charcot to Kribi). Basins of segments 3, 4, and 5 make-up the Sinistral domain of the Central Salt Basins (CSB´s).

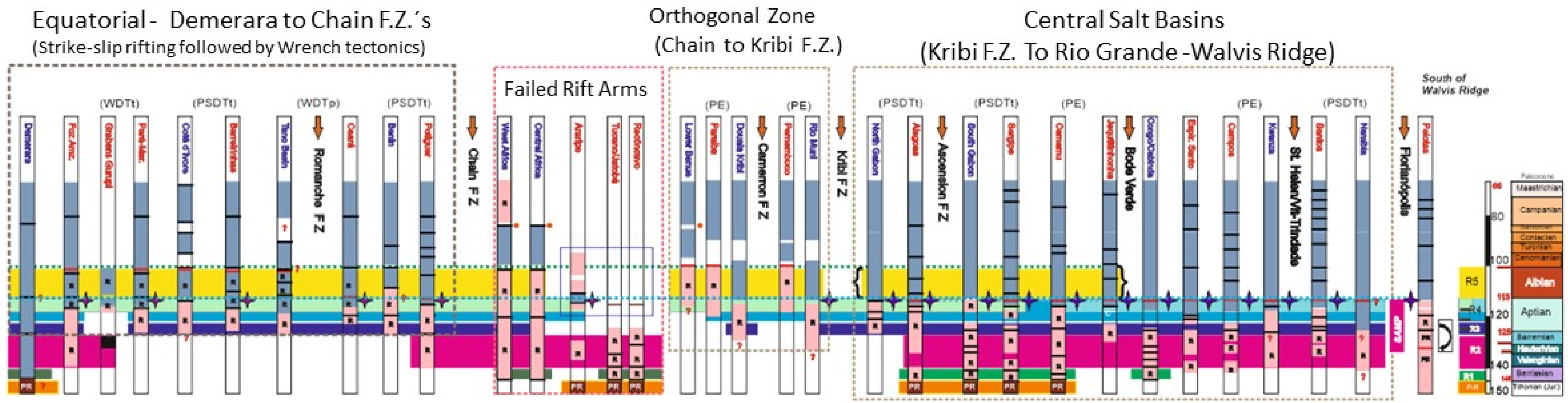


Figure 3. Kinematic changes in space and time of the Equatorial and South Atlantic. The horizontal axis follows the spatial domain, from Demerara (left) to Florianopolis Fracture Zone (right). The vertical axis shows the time span of each kinematic stage, as well as providing key observations regarding depositional environments, continental or marine rifting and the onset of sea-floor spreading. (See symbology definitions in Figure 4). Buffer zones with linked transforms are not reflected on the figure and in symbology.

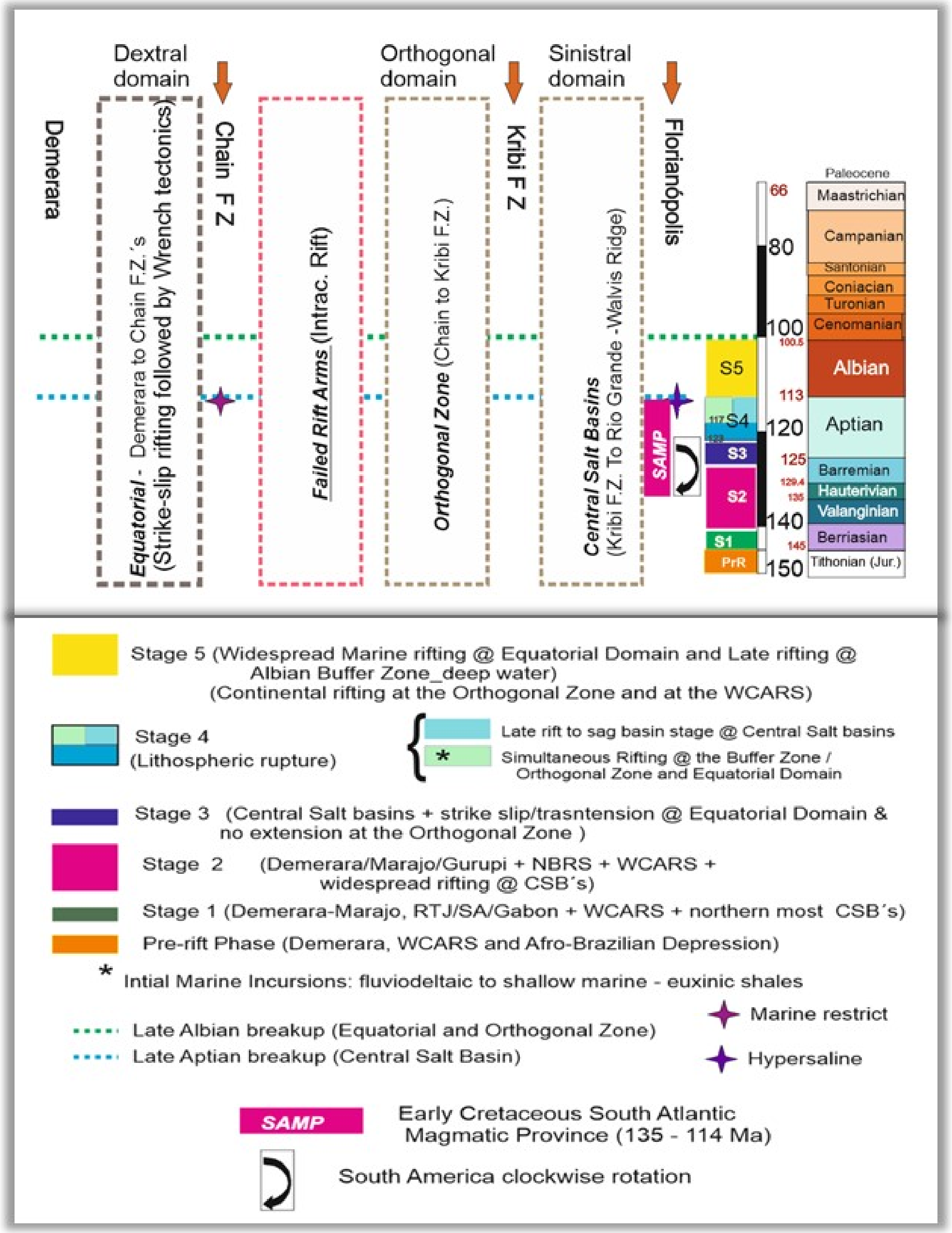


Figure 4. Interpreted kinematic stages, with symbology explained.

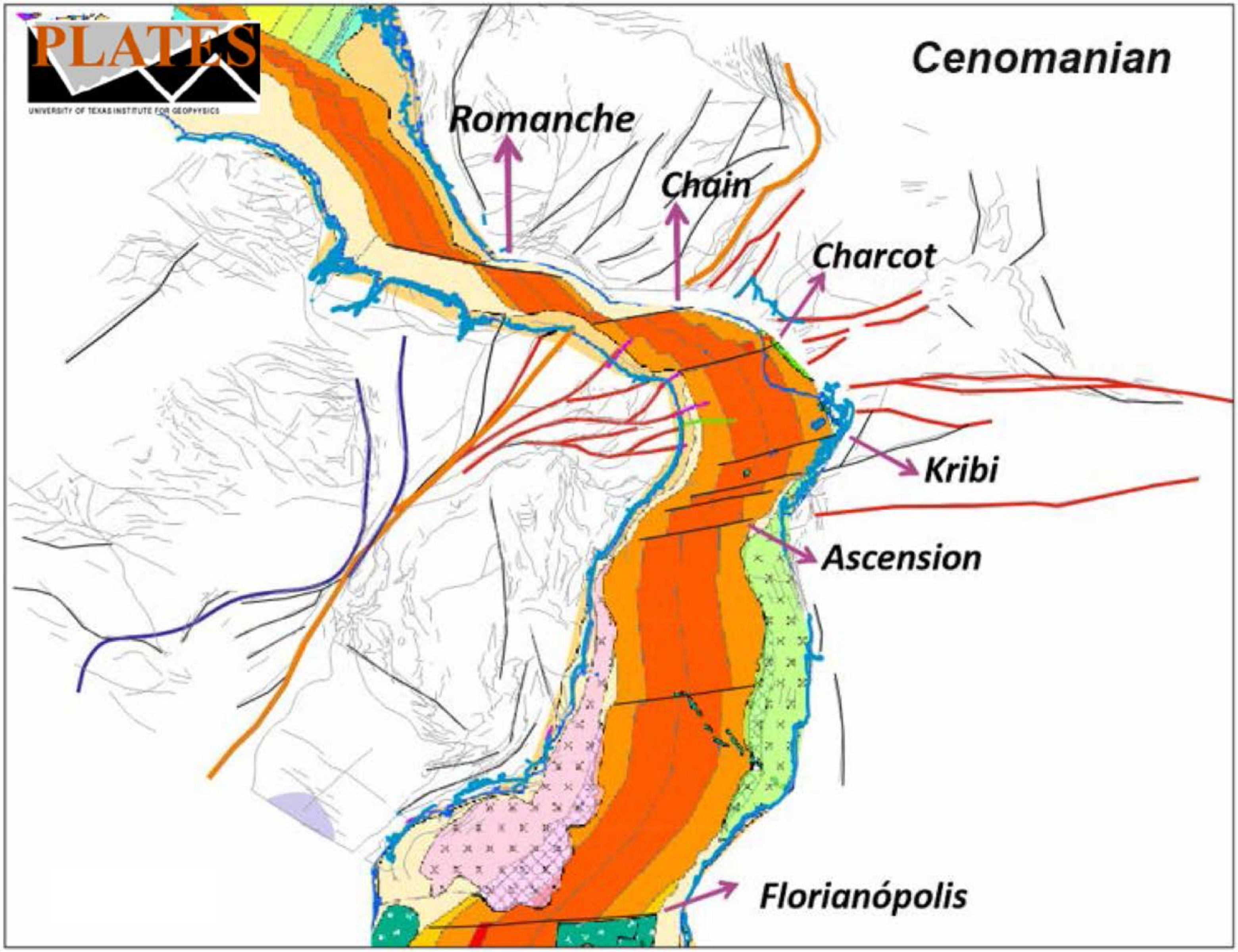


Figure 5. Schematic figure of the South Atlantic Ocean during the Cenomanian, with the main Proterozoic features and the location of active sea-floor spreading and fracture zones. The Brazil salt basin is in pink; the African salt basin in green. Red to orange shades show age of oceanic crust. Green pattern is the Walvis Ridge and Pelotas volcanic margin.