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Brazilian and African passive margins of the Central Segment of the South Atlantic Ocean: Kinematic constraints

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ABSTRACT

The thinning of passive continental margins is usually explained by models using pure stretching or simple shear. These models imply hypothetical extensional structures and large horizontal movements between the two conjugate margins (more than 250 km for the Brazilian and Angolan Margins). Refraction/reflection data together with the most recent and tightest pre-opening fit using continental and oceanic, geological and geophysical constraints show that the substratum of the sag basin is divided into an autochthonous part (upper continental crust) and an allochthonous part (exhumed material). The thinning process, which evolves in an elevated position of the system until at least the break-up, seems to be depth dependent and to mainly concern the lower/middle crust, which we postulate is exhumed. This exhumation does not explain the entire thinning of the system: horizontal motions cannot alone explain the formation of the huge Angolan–Brazilian Basin. Similar observations are made on the whole Central Segment of the South Atlantic Ocean. Part of the lower continental crust is still missing and it seems most improbable that the continental crust maintains its integrity throughout the thinning process.

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1. Introduction

In 1978, in his famous article "*Some remarks on the development of sedimentary basins*", McKenzie wrote the foundations of what has been, until today, the root of the understanding of continental crust thinning and the genesis of so-called passive continental margins. Since and despite the existence of many different hypotheses (see Keen and Beaumont, 1990, for a review), "conservative" models (i.e. models where the volume of the continental crust is preserved during the process) were largely invoked to explain the transition between a normal continental crust and an oceanic crust.

Two end-member conservative models exist: pure stretching (McKenzie, 1978) and simple shear (Wernicke, 1985; Lister et al., 1986). Pure stretching extension generally implies symmetric conjugate margins and the extension in the upper crust is characterized by tilted blocks (McKenzie, 1978). Margins formed by shear extension, with simple (Wernicke, 1985) or multiple detachment surfaces (Lister et al., 1986), will be asymmetric, with an "upper plate" with tilted blocks on one side and a "lower plate" on the other side. A number of combinations of the two original models have also been proposed with spatial, temporal variations or with two layers behaving differently (depth-dependent stretching beside simple shear), but the principle of continental crust conservation still applies.

Quantitative modelling provides predictions that should be tested against observations. If sound agreement is found between observations and predictions, the initial hypothesis is still possible. If not, the hypothesis is not valid.

Whatever the conservative model, two main problems still remain: 1) as McKenzie (1978) noticed: "*the most obvious objection to the model discussed in the last section is that the large amounts of extension required to produce the observed subsidence have not been described*". Thirty years later, this observation is still relevant in most cases. Except for very particular margins with complicated geodynamic history, only very few tilted blocks are clearly observed, usually on the upper part of the slope or at its toe (Moulin et al., 2006). These blocks cannot explain the thinning and the amount of subsidence observed.

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Moreover, crustal thinning appears to occur abruptly: its thickness decreases from more than 30 km to about 7 to 10 km, over a lateral distance of usually less than 70 km (as for instance in Atlantic Oceans: the Spitsberg margin: Ritzmann et al., 2002, 2004; the Gulf of Biscay: Thinon, 1999; Thinon et al., 2003; the Flemish Cap and Grand Banks–Newfoundland Margins: Lau et al., 2006; Hopper et al., 2006; the Angolan Margin: Contrucci et al., 2004; Moulin, 2003; Moulin et al., 2005; the Moroccan Margins: Labails, 2007; Labails et al., this issue; Klingelhoefer et al., this issue. 2) Conservative models intrinsically imply important horizontal movement whose consequences will have to be observed in the field.

The horizontal movement is not usually constrained in models whilst it is one of the main parameters to be considered, especially for conservative models (pure stretching, simple shear, multiple shears and all their combinations…). This paper focuses on this point: it replaces the seismic results of the Zaiango experiment in a kinematic context in order to constrain horizontal movement and to discuss the consequences on passive margin genesis. It shows that plate tectonics does not only "*provide a useful framework for description of margins*" (Keen and Beaumont, 1990) but is also a useful constraint to understand the genesis of passive margins.

2. The Central Segment of the South Atlantic Ocean and the Campos–Angolan System

Passive continental margins are so diverse that the existence of a unique thinning process must be questioned. All passive continental margins do not present the same complexity, depending on previous tectonic history (i.e. tectonic heritage) and the complexity of its geodynamic history (single-phased or multi-phased). At the same time, the visibility of the structures depends on the accessibility of geophysical and geological data, including refraction/reflection seismic, gravity, dredges, drills, magnetism and kinematical constraints, both onshore and offshore. The presence of seismic screens, like salt, carbonates or volcanism, is often a serious handicap. Lastly, a single margin is only half of the system: the conjugate margin needs to be clearly identified by precise initial kinematic reconstructions and sampled with similar methods and accuracy. Therefore, a real typology of passive margins around the world is needed. We provide here data and conclusions on a large piece of the jigsaw, a segment of more than 2000 km, on both sides of the Central Segment of the South Atlantic Ocean.

The South Atlantic Ocean is divided into four segments (Fig. 1; the Falkland segment, south of Agulhas–Falkland Fracture zone, is not shown). The Central Segment, between the Rio Grande Fracture zone and the Ascension Fracture Zone, is characterized by the presence of an approximately 1–2 kilometre-thick salt layer (Brognon and Verrier, 1966; Masson, 1972; Brice et al., 1982; Giresse, 1982; Teisserenc and Villemin, 1990), overlying a mainly non-marine sequence; both layers are overlain by marine shale and carbonates (for instance, Burke and Dewey, 1974; Doyle et al., 1977, 1982; Mussard, 1996). This evaporite layer was commonly ascribed to a deep confined deposition due to a physical barrier (the Rio Grande–Walvis Ridges System) restricting marine water exchange. Recently, Karner and Gambôa (2007) invoked a climate-induced deep-lake level drawdown as "*a simple mechanism to generate the shallow water environments for evaporite precipitation*". Such a drawdown, as the well known and described Messinian event in the Mediterranean Sea, has dramatic consequences on sediment layers: erosional surface on the platform and the emerged parts of the continental slope, salt layer only in the deep basin (Guennoc et al., 2000; Rouchy et al., 2006; also see Bache, 2008, for a recent synthesis of the huge amount of publication on this event). As already shown by Moulin (2003) and Moulin et al. (2005), the presence of salt cover continuously from the platform to the deep basin, together with the absence of thick marine layers prior to Aptian times and the absence of an erosional surface contemporaneous to salt deposition indicate that salt was not deposited in a deep confined marine/lake context (like in the Mediterranean Sea), but is related to the first marine transgression in a shallow lagoon environment. The presence of carbonates overlying the salt layer (for instance, Burke and Dewey, 1974; Doyle et al., 1977, 1982; in Mussard, 1996) furthermore shows that this shallow environment lasted after the salt deposition.

The break-up of the Central Segment of the South Atlantic Ocean during the so-called quiet magnetic period of the Cretaceous and the presence of the thick Aptian salt layer on its margins (Fig. 1) appear as unfavourable factors to study the continental thinning process in this area.

These points are in fact not as troublesome as they would appear; they can be overcome and even present some advantages:

- The lack of magnetic data in the Central Segment is largely compensated for by the presence of well-marked fracture zones, especially in the Equatorial Segment, and by the presence of the Demerara and Guinean conjugate plateaux and onshore conjugate lineaments (Fig. 1, blue lines). These morphological elements, combined with the knowledge of the intra-plate deformation on both continents, allow precise pre-break-up kinematic reconstruction and therefore tightly constrain the horizontal movement of the involved plates (Moulin, 2003; Moulin et al., 2007).
- The Aptian salt layer, which indeed represents a seismic screen, is present all across the margin up to the platform and subsequently represents a useful paleo-bathymetric marker for vertical reconstruction of margin history as it is related to the first marine transgression in a shallow lagoon environment (Moulin et al., 2005).

Moreover, the margins of the Central Segment present some particular advantages:

- The margins of the North Atlantic Ocean, including the Newfoundland and Iberian Margins, present two distinct episodes of rifting: in Permian–Trias periods, distension occurred and aborted in Occidental Europe and gave rise to the deposition of evaporites (Ziegler, 1988; 1989 for a general view); in the middle Cretaceous period, another distension occurred and broke the system apart. More than 70 Ma separate these two episodes, which strongly complicate the interpretation of thinning processes. On the contrary, the break-up of the Central Atlantic occurred in a single episode, at the Trias–Lias boundary (Sahabi et al., 2004), and the margins of the Central Segment of the South Atlantic Ocean were formed during a single episode of rifting.
- This rifting occurs on the location of the Panafrican suture, more than 450 Ma after its formation: In the South Atlantic Ocean, the two events are clearly dissociated. In comparison, the Atlantic Central rifting, at the end of Sinemurian (Sahabi et al., 2004), strictly follows the end of the Hercynian suture.
- New precise refraction/reflection seismic data were collected on the Angolan Margin (Contrucci et al., 2004; Moulin et al., 2005). Refraction seismic data do not exist on the conjugate Brazilian Margin. However, several deep reflection seismic profiles were acquired on the Brazilian Margin during the late 1980s and early 1990s (Mohriak and Latgé, 1991; Rosendahl et al., 2005) and dense networks of industrial reflection seismic profiles on both sides of the ocean compensate for this lack of refraction data.

2.1. Previous interpretations of the Brazilian–Angolan Margins

As on most continental passive margins throughout the world, conservative thinning models were prevalently invoked to explain the formation of the Brazilian–Angolan Margins.

The pure stretching model was first applied to the Santos Basin (Chang and Kowsmann, 1984), then to the Sergipe–Alagoas Basin (Chang and Kowsmann, 1986; Pontes et al., 1991; Mohriak et al.,

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