Conjugate Divergent Margins

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Abstract:

Conservational models, like simple shear, pure shear or polyphase models that exclude exchanges between the lower continental crust and upper mantle, are usually proposed to explain the lithospheric stretching and consequent crustal thinning of passive continental margins. These models need large amounts of horizontal movement, and have, therefore, important implications for plate kinematic reconstructions and intraplate deformation. In this paper we propose to show these implications in the Central Segment of the South Atlantic Ocean. In the Angola–Brazilian system, these models imply about 240 km of horizontal movement. This movement can be compensated by two end-member mechanisms: (1) an intraplate deformation located in Africa; and (2) an intraplate deformation located in South America. We detail for each solution the strong geological and geodynamical implications, and discuss the consequences for the genesis of passive continental margins.

I) INTRODUCTION

Since the classical models of McKenzie (1978) and Wernicke (1985), understanding the formation of continental passive margins, that is to say mainly the way that continental crust thins, is one of the main challenges of Earth Sciences. The deep water hydrocarbon discoveries, the high position of the margin until the break-up and even more later (Moulin et al., 2005; Aslanian et al., 2009; Labails et al., 2009; Péron-Pinvidic & Manatschal, 2009; Bache et al., 2010), the absence of extensive faults (Moulin et al., 2005; Unternehr et al., 2010), the anomalous heat flow in the transitional domain (Dupré, 2003, Lucazeau et al., 2008, Lucazeau et al., 2010) the discovery of

serpentinized mantle (Boillot *et al.*, 1980), and the fact that some part of lower crust is missing in the process (Aslanian *et al.*, 2009) have modified the basic concepts of margin formation. Efforts were done in numerical modelling in order to explain the presence of exhumed mantle observed in few places or the wide transitional domain and/or the sag-basin (Lavier & Manatschal, 2006; Kuszniir & Karner, 2007 ; Huismans & Beaumont, 2008; Reston, 2010; Huismans & Beaumont, 2011). Nevertheless, very few works have shown these models in precise paleogeographic maps and in global paleogeographic evolution and have analysed the drastic implications of their inherent horizontal movement in terms of kinematic reconstructions and intraplate deformation. Though, whatever the conservative model (for instance: McKenzie, 1978 Wernicke, 1985, Lavier & Manatschal, 2006, Reston, 2010), it needs huge amount of horizontal movement that has to be tested independently.

II) CONSERVATIVE VERSUS NON-CONSERVATIVE MODELS.

Recurrently, within a conceptual approach, conservative models are proposed to explain the passive margin genesis: a model built on one particular margin is applied to many other margins, with a model-dependant analysis of the data and without questioning the problem of horizontal movement in a global kinematic setting. In terms of horizontal movement, that is to say in terms of kinematic reconstruction, the problem of conservative models is purely geometrical: if no exchange between the continental crust and upper mantle is allowed, if no lower continental crust flow is involved, the continental crust thinning process can directly be converted in horizontal movement (the actual volume of continental crust is strictly equal to the initial volume, before any horizontal movement). Figure 1-A illustrates this geometrical problem of this conceptual approach with the simplified geometries of the conjugate Angola and Esperito Santo continental passive margins (Contrucci *et al.*, 2004; Moulin *et al.*, 2005; Aslanian *et al.*, 2009, Unternehr *et al.*, 2010). If the entire intermediate thin domain ($L_{act} * H_{act}$) represents stretched continental crust, the horizontal movement to reconstruct the initial system ($L_0 * H_0$) will be : $L_{act} * (1 - H_{act} / H_0)$. In the central segment of the South Atlantic Ocean, this horizontal movement will be as great as 240km (Aslanian *et al.*, 2009). This amount will be of course greater if some parts of the intermediate domains have a different nature than continental, for instance serpentinized mantle as recently proposed by Unternehr *et al.*, 2010 (equal to $L_{act} - 300\text{km}$ in the case of the central segment of the South Atlantic Ocean - if no part of the intermediate domain is continental). On the other hand, Figure 1-B illustrates the same problem, but with a supplementary and independent constraint: the kinematic constraint. Figure 1-B-2) represents the initial system in the tightest reconstruction

given by the kinematic constraints. In the central segment of the South Atlantic Ocean, the tightest reconstruction given by Moulin *et al.* (2010) implies about 100km of horizontal movement only. Based on that precise kinematic reconstruction, Aslanian *et al.* (2009) proposed a different, non-conservative evolution of the passive margins with two options whether the part 2, called the allochthonous domain, is continental (Figure 1-B-2) or non continental (exhumed mantle, atypical oceanic crust, intruded continental crust – Figure 1-B-3). In both case anyway, a large amount of lower crust is missing and the thinning process, which evolves in an high position until at least the break-up, seems to be depth dependent and mainly concerns the lower part of the continental crust (Aslanian *et al.*, 2009).

We propose here to test these conservative models (the conceptual approach: Figure 1-A) in the central segment of the South Atlantic Ocean and highlight their consequences on plate tectonic and intraplate deformation.

III) GEODYNAMICAL CONTEXT FOR THE INITIAL SYSTEM OF MARGINS

In 2009, Aslanian *et al.* presented three synthetic initial systems of conjugate margins of the central segment of the South Atlantic Ocean situated in the tightest reconstruction proposed by Moulin *et al.* (2010), before the beginning of the rifting. Their approach was to use all information given by geophysical data in order to draw the actual geometry of some conjugate margins, then to restore palinspatic profiles at the time of their genesis and to replace them in a precise and global kinematic reconstruction without any a priori conceptual model. Figure 2 shows this restitution in a more global view, including the initial geometry of two conjugate systems of the Austral segment of the South Atlantic ocean: the Pelotas – Walvis System, based on industrial profile (Moulin *et al.*, 2006) and Transect 2 profile (Bauer *et al.*, 2000) and the Argentine – Orange System, based on the BGR98-41 (Franke *et al.*, 2007) and BGR98-REF1 profiles (Franke *et al.*, 2006) and the Springbok profile (Hirsch *et al.*, 2009). Transect2 (Namibia) and Springbok (South Africa) crustal geometries are constrained by refraction data (Bauer *et al.*, 2000; Hirsch *et al.*, 2009), as well as the less distal part of the Argentina Profile (Colorado basin), whereas gravity modelling approximates the crust geometry of the other profiles, using available neighbouring velocity model (Franke *et al.*, 2002 and Franke *et al.*, 2006, for the Argentina margin and Colorado basin profiles). As it was done for the systems of the central Segment, we projected those profiles on flowlines and used the Seaward Dipping Reflectors (SDRs, Hinz, 1981; Austin & Uchupi, 1982; Gerrard & Smith, 1982; Gladchenko *et al.*, 1997; Hinz *et al.*, 1999; Bauer *et al.*, 2000; Franke *et al.*, 2007) and the thick piles of sub-aerial lava flows that represent volcanic

activity during rifting (Hinz, 1981; Austin, 1990; Talwani *et al.*, 1995) as a paleobathymetric markers. The intraplate deformations in the Africa and South America plates, based on all available geophysical, geological, which were used to built this reconstruction, are shown on the kinematic reconstruction of the figure 2 (see Moulin *et al.*, 2010, for more explanations). This figure represents therefore 5 systems of conjugate margins of the South Atlantic Ocean in the tightest reconstruction and represents the case B-2 of the figure 1. In each system, the parts 2 of intermediate domain, called “allochthonous crust” by Aslanian *et al.* (2009), overlap each other and are not shown. The red areas represent the missing lower continental crust for each system, as on Figure 1.

If we follow the conceptual approach and apply any conservative model on those systems, we need supplementary horizontal movement to explain the missing continental crust and reconstruct the unthinned systems (Figure 1-A), that is to say that the reconstruction given by Moulin *et al.* (2010) is not the tightest one.

Aslanian *et al.*, 2009, have shown that the conservative models imply a remaining space between the two hinge lines of about 130 km, instead of 280 km in the reconstruction of Moulin *et al.*, 2010, and therefore need 150km additional horizontal movement. Anyway, the kinematic problem consists not only of finding a solution to reduce a distance on a specific area (the boundary between two blocks) but must also focus on the consequences of this solution on the faraway limits of this blocks: a small difference in position on that limit can have indeed drastic consequences on the distant boundaries of the plates (see Figure 14 in Moulin *et al.*, 2010) and we propose to show in the next sections what happens if we try to constrict this reconstruction in order to fit the conservative models.

25

26 **Definition of the pieces of the jigsaw puzzle**

27 In the Austral segment, on the so-called rich-magma margins, the presence of the magnetic anomalies (LMA) determined on base of all new magnetic data available, constrains the reconstruction at the end of the rifting, just before the seafloor spreading (Moulin *et al.*, 2010). We do not have any constraint on the “pre-opening position” stage. In Figure 2, the Pelotas-Walvis conjugate margins presents an almost unthinned system, which blocks this part of the Austral Segment of the South Atlantic Ocean. The huge quantity of the « missing » lower continental crust on the Argentine-Orange systems can therefore be explained, in a case of conservative model, by a rotation of the Colorado and Argentina sub-plates. This rotation will produce a large strike-slip movement that is not observed in the Salado Basin, which seems to falsify this hypothesis. Anyway, this question does not interfere with the kinematic problem of the central segment, our

37 focused area, where conservative models are proposed (Unternher *et al.*, 2010; Reston, 2010,
38 Lentini *et al.*, 2010) and we will consider in the rest of this study the Patagonia, Salado, Argentina
39 and Rio Plata sub-plates fixed in respect to the Austral African sub-plate, in their position just
40 before the rifting with the best adjustment between the two “Large Marginal Anomalies” (Figure
41 3).

42 Due to very good parallelism of the coastlines that tends to prove the absence of deformation
43 in the Guyana and West African Precambrian shields, and the adjustment of the Demerara and
44 Guinean plateaux as well as the alignment of the Kandi and Sobral lineaments, no further
45 movement can be applied to the Equatorial segment (Moulin *et al.*, 2010) and Figure 2 presents
46 this area in its tightest position, which therefore represents an incompressible zone: the West
47 African and the Guyana sub-plates will be therefore considered fixed to each other (Figure 3).

48 In terms of geometry, two end-member solutions could allow to constrict the reconstruction given
49 in Figure 2: 1) all intraplate deformation would take place in the Africa Plate 2) all intraplate
50 deformation would take place in the South America Plate. All Figures in this paper are drawn with
51 the West Africa and Guyana as the referential block (West Africa and Guyana block is considered
52 to be fixed). All this kinematic work was conducted using the open-source PLACA software
53 (Matias *et al.*, 2005). This software was developed for earth scientists working on the plate
54 tectonics theory. It enables the representation of plate reconstructions and the determination of
55 best-fit poles using magnetic anomalies, fracture zones or volcanic alignments. The best-fit poles
56 can be computed either visually (for example with the method of Olivet (1978) and Bonnin
57 (1978)) or by systematic routine search. Once the best-fit pole is obtained, several statistical tests
58 can be made to evaluate the confidence of the fit. This code is free of access at
59 http://www.ifremer.fr/drogm/telechargement/placa_version_0_1.

60

61 **The case of Africa Plate deformation**

62 In Figure 4, all sub-plates are in the same position than in Figure 2, except the Austral African
63 sub-plate and the four southern American sub-plates: Rio Plata, Argentina, Patagonia and Salado
64 which we consider as single block (see above). This block has been rotated in order to reduce the
65 space between the two hinge lines in the central segment to 150-160 km as conservative models
66 imply (Table 1). This motion tries also to respect the strike-slip deformation along the Central
67 African Shear Zone described by Cornachhia & Dars (1983), Fairhead (1988) and Benkhelil
68 (1988). Nevertheless several problems arise in that configuration:

69 1) The hinge lines, between the North Gabon and Sergipe margins in the northern part of the

central segment, are face to face, which not allow enough room for the intermediate domain of the both conjugate margins: in that case, the intermediate domain (about 100km on the Sergipe margin) must be allochthonous and the thinning very sharp as on Transform Passive Margin. These margins are nevertheless oblique.

2) The boundary between the Santos and the Rio de la Plata sub-plates, in the Paraná area, is described as an extensional-dextral shear zone (Conceição *et al.*, 1988). It is hidden by the huge Early Cretaceous Serra Geral volcanism of Paraná Basin, but it is described a serie of linear tectonic faults (Zalán *et al.*, 1990) and Eyles & Eyles (1993) inferred, from a sub-surface study of the upper Paleozoic glaciogenic infill, the possible existence of a 150 km dextral strike-slip movement in the Paraná Basin. The configuration given by Figure 4 creates a 40 km sinistral strike slip movement and the amount of extension inside the Paraná basin increases twofold to 125-200km.

3) Last but not least, this reconstruction implies a compression up to 100 km in the area of the Sudan rifts where extension is described (Fairhead, 1988; Jorgensen and Bosworth, 1988). This additional motion of the Austral African plate is comparable with the model proposed by Pindell & Dewey (1982). As Unternehr *et al.* (1988) have already noticed, this kind of rotation is not in agreement with the geological observations in the Sudan area. To avoid this, we can rotate the Nubian plate but this rotation will imply compression in the Tenere basin and in the area of 10°East and Amguid-Gassi Touil-Alagerian lineaments where respectively, extension (Fairhead, 1988) and transpressive deformation (Boudjema, 1987; Guiraud & Maurin, 1992) are described.

The case of South America Plate deformation

In Figure 5, all sub-plates are in the same position than in Figure 2, except the São Francisco and the Santos sub-plates, which have been rotated in order to minimize the space between the two hinge lines in the central segment at 150-160 km (Table 2). This configuration eliminates the 150km dextral strike-slip deformation in Paraná area but two main problems arise:

1) The motion of the São Francisco plate implies 90 – 140 km of extension in the only 70-80km wide, asymmetrical, eastward tilted half-graben Tucano – Reconcavo – Jatoba basins (Magnativa, 1992; Magnavita & da Silva, 1995). This incompatibility with the geological observations could be avoid by a rotation of the Tucano sub-plate, but this will produce transpressive movement in Pernambuco area which is not observed on field.

2) This configuration produces a compression increasing towards the south – west (100 to 400 km) along the area delimited by the Transbrasiliano lineament and in the Andean Cordillera virgation: the 125 km of compression induced by the initial reconstruction of Moulin *et al.* 2010 in

04 the corner of the Bolivian orocline to the middle of the foreland basin of Bolivia and Brazil are
05 already problematic, even if some evidences exist of cretaceous compressive deformation
06 (Mpodozis and Ramos, 1990, in Allmendinger & Gubbels, 1996; Martinez & Vargas, 1988),
07 400km are completely incompatible with the geological observations in the Central Andean area.
08 Moreover, no compressive deformation is observed along the dextral Transbrasiliano shear zone
09 (Fairhead & Maus, 2003; Ngako *et al.*, 2003; Attoh & Brown, 2008). In order to avoid this
10 problem, we could break up the Guyana-West Africa block and rotate the Guyana subplate with
11 respect to the fixed West Africa subplate, but this creates 150km of compression between the
12 Demerara and Guyana plateaux, where there are no traces of such deformation.

13

14 IV) DISCUSSION

15 Both end-member solutions produce serious intraplate deformations on both African and South
16 America plates, which are not in agreement with the actual geological observations. The
17 application of these solutions needs at least to be tested with field studies. Anyway, it seems
18 difficult to find strong traces of overall compression in rift area, like in Sudan rift system, and it is
19 worth to note that a compression of 150 km was enough to produce the Pyrenees Mountains.

20 Another solution would be to distribute the deformation all over both Africa and South America
21 Plate (for instance Torsvik *et al.*, 2009, following the reconstruction of Müller & Nürnberg, 1991,
22 in the central segment). In such configuration, the intraplate problem is less important, place by
23 place, but spread out on several areas which are all in disagreement with the actual geological
24 observations (Aslanian & Moulin, 2010, Torsvik *et al.*, 2010, Moulin & Aslanian, 2010).

25 Aslanian *et al.* (2009) already pointed out, that conservative models are not able to explain all the
26 observations collected in the South Atlantic conjugate Margins. The thinning process seems to be
27 depth dependent and to mainly concern the lower/middle crust which seems to be exhumed but
28 this exhumation does not explain the entire thinning of the system (the red areas on figure 1 and
29 2): horizontal motions cannot alone explain the formation of the conjugate margins systems in the
30 Central Segment of the South Atlantic Ocean. It seems not possible that the continental crust
31 would maintain its integrity throughout the thinning process: the conservative models, like the one
32 proposed by Unternehr *et al.*, 2010 following the model of Lavie & Manatschal (2006) on the
33 Iberia-Newfoundland conjugate margins, can not be applied here. These observations were
34 recently supported by new numerical modellings (Huisman & Beaumont, 2011), which classify
35 margins into two different end-members (Type I : Iberia-Newfoundland ; Type II : Central
36 segment of the South Atlantic Ocean).

37 This study shows that all propositions, all conceptual models must be situated on precise

paleogeographic maps and evolution in order to test their consequences on global view and to be validated. This needs to avoid « conceptual kinematic models » on small sketches and can be only done by precise kinematic reconstructions with properly calculated Eulerian Poles.

1-

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REFERENCE

- Allmendinger, R.W. & Gubbels, T., 1996. Pure and simple shear plateau uplift, Altiplano-Puna, Argentina and Bolivia, *Tectonophysics*, 259, 1-13.
- Aslanian, D., Moulin, M., Olivet, J.-L., Unternehr, P., Matias, L., Bache, F., Rabineau, M., Nouzé, H., Klingelhoefer, F., Contrucci, I. & Labails, C., 2009. Brazilian and African passive margins of the Central Segment of the South Atlantic Ocean: kinematic constraints, *Tectonophysics (Special Issue: role of magmatism)*, 468, 98-112, [doi:10.1016/j.tecto.2008.12.016](https://doi.org/10.1016/j.tecto.2008.12.016).
- Aslanian, D. & Moulin, M., 2010. Comment on 'A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin' by Torsvik, Rouse, Labails & Smethurst, accepted to *Geophysical Journal International*, DOI: [10.1111/j.1365-246X.2010.04727.x](https://doi.org/10.1111/j.1365-246X.2010.04727.x)
- Attoh, K. & Brown, L.D., 2008. The Neoproterozoic Trans-Saharan/Trans-Brasiliano shear zones: Suggested Tibetan Analogs, American Geophysical Union, Spring Meeting, abstract #S51A-04.
- Austin, J. A. & Uchupi, E., 1982. Continental-oceanic crustal transition off Southwest Africa. *American Association of Petroleum Geologists Bulletin*, 66: 1328-1347.
- Austin, J.A., Stoffa, P.L., Phillips, J.D., Oh, J., Sawyer, D.S., Purdy, G.M., Reiter, E., Markis, J., 1990. Crustal structure of the Southeast Georgia embayment–Carolina Trough: preliminary results of a composite seismic image of a continental suture (?) and a volcanic passive margin. *Geology*, 18, 1023–1027.

72 Bache F., Olivet J.-L., Gorini, C., Aslanian, D., Labails, C., Rabineau M., 2010. Evolution of rifted
73 continental margins: The case of the Gulf of Lions (Western Mediterranean Basin), *Earth and*
74 *Planetary Research Letters*, vol. 292, 3-4, 345-356.

75 Bauer, K., Neben, S., Schreckenberger, B., Emmermann, R., Hinz, K., Fechner, N., Gohl, K., Schulze, A.,
76 Trumbull, R.B. & Weber, K. 2000. Deep structure of the Namibia continental margin as derived
77 from integrated geophysical studies. *Journal of Geophysical Research*, 105: 25829-25853.

78 Benkhelil, J., 1988. Structure et Evolution du bassin de la Bénoué. *Bulletin des Centres de Recherches*
79 *Exploration-Production*, Elf Aquitaine 12: 29-128.

80 Boillot, G., Grimaud, S., Mauffret, A., Mougenot, D., Kornprobst, J., Mergoïl-Daniel, J. & Torrent, G.
81 1980. Ocean–continent boundary off the Iberia margin: a serpentinite diapir west of the Galicia
82 Bank. *Earth and Planetary Science Letters*, 48, 23–34.

83 Bonnin, J. 1978. Evolution géodynamique de la ligne Açores-Gibraltar. Paris, Univ. Paris VII: 144 pp.

84 Boudjema, A., 1987. Evolution structurale du bassin pétrolier « triasique » du Sahara Nord oriental Algérie.
85 Thèse, Univ. Paris Sud, Paris, 290 pp.

86 Conceição, J. C. de J., Zalán, P. V. & Wolff, S., 1988. Mecanismo, Evolução e cronologia do rift sul-
87 atlântico (Mechanism, evolution and chronology of South Atlantic Rifting). *Bol. Geoci. Petrobras*,
88 *Rio de Janeiro*, 2 (2/4): 255-265.

89 Contrucci, I., Matias, L., Moulin, M., Géli, L., Klingelhoeffer, F., Nouzé, H., Aslanian, D., Olivet, J.-L.,
90 Sibuet, J.-C. & Réhault, J.-P., 2004. Deep structure of the West African continental margin, between
91 5°S and 8°S, from reflection / refraction seismics and gravity data. *Geophysical Journal*
92 *International*, 158 : 529-553.

93 Cornacchia, M. & Dars, R., 1983. Un trait structural majeur du continent africain. Les linéaments
94 centrafricains du Cameroun au Golfe d'Aden. *Bulletin de la Société Géologique de France*, 1: 101-
95 109.

96 Dupré, S., 2003. Integrated tectonic study of the South Gabon Margin: Insights on the rifting style from
97 seismic, well and gravity data analysis and numerical modelling, Ph. D Thesis, *Vrije University*,
98 Amsterdam, 125 pp.

99 Eyles, N. & Eyles C. H. 1993. Glacial geologic confirmation of an intraplate boundary in the Paraná basin
00 of Brazil. *Geology*, 21, 459-462.

01 Fairhead, J. D. 1988. Mesozoic plate tectonic reconstructions of the central South Atlantic Ocean: The role
02 of the West and Central African rift system. *Tectonophysics*, 155: 181-191.

03 Fairhead, J. & Maus, S., 2003. CHAMP satellite and terrestrial magnetic data help define the tectonic
04 model for South America and resolve the lingering problem of the pre-break-up of the South Atlantic
05 Ocean. *The Leading Edge*, 779-783.

06 Franke, D., Neben, S., Hinz, K., Meyer, H. & Schreckenberger, B., 2002. Deep Crustal Structure Of The
07 Argentine Continental Margin From Seismic Wide-Angle And Multichannel Reflection Seismic

Data. *AAPG Hedberg Conference "Hydrocarbon Habitat of Volcanic Rifted Passive Margins"*, September 8-11, 2002, Stavanger, Norway.

Franke, D., Neben, S., Schreckenberger, B., Schulze, A., Stiller, M. & Krawczyk, C.M. 2006. Crustal structure across the Colorado Basin, offshore Argentina. *Geophysical Journal International*, doi: 10.1111/j.1365-246X.2006.02907.x: 1-15.

Franke, D., Neben, S., Ladage, S., Schreckenberger, B. & Hinz, K., 2007. Margin segmentation and volcano-tectonic architecture along the volcanic margin off Argentina/Uruguay, South Atlantic. *Marine Geology*, 244: 46-67, doi:10.1016/j.margeo.2007.06.009.

Gerrad, I. & Smith, G. C., 1982. Post-Paleozoic succession and structure of the southwestern African continental margin. *American Association of Petroleum Geologists Memoir*, 34 : 49-74.

Gladchenko, T. P., Hinz, K., Eldholm, O., Meyer, H., Neben, S. and Skogseid, J., 1997. South Atlantic volcanic margins, *Journal of the Geological Society*, London, v. 154, 465-470.

Gradstein, F. M., Ogg, J. G. & Smith, A. G., 2004. A Geologic Time Scale. Cambridge.

Guiraud, R. & Maurin, J.C., 1992. Early Cretaceous rifts of Western and Central Africa: an overview, *Tectonophysics*, 213: 153-168.

Heilbron, M., Mohriak, W. U., Valeriano, C. M., Milani, E. J., Almeida, J. and Tupinambá, 2000. From collision to Extension: The roots of Southeastern Continental Margin of Brazil, in W. Mohriak and M. Talwani, eds., *Atlantic Rifts and Continental Margins*, AGU 115, 1-32.

Hinz, K., 1981. A hypothesis on terrestrial catastrophes: wedges of very thick oceanward dipping layers beneath passive continental margins. *Geol. J.* E22: 3-28.

Hinz, K., Neben, S., Schreckenberger, B., Roeser, H. A., Block, M., Goncalves de Souza, K. & Meyer, H., 1999. The Argentine continental margin north of 48 degrees S; sedimentary successions, volcanic activity during breakup. *Marine and Petroleum Geology*, 161: 1-25.

Hirsch, K. K., Bauer, K. & Scheck-Wenderoth M., 2009. Deep structure of the western South African passive margin – Results of a combined approach of seismic gravity and isostatic investigations. *Tectonophysics*, 470: 57 – 70, doi:10.1016/j.tecto.2008.4.028

Huismans, R.S. & Beaumont, C., 2008. Complex rifted continental margins explained by dynamical models of depth-dependent lithospheric extension. *Geology*, 36: 163-166.

Huismans, R.S. & Beaumont, C., 2011. Depth-dependent extension, two-stage breakup and cratonic underplating at rifted margins, *Nature*, 473: 74-78, doi:10.1038/nature09988.

Jorgensen, G.J. & Bosworth, W., 1988. Gravity modelling in the Central African Rift System, Sudan: Rift geometries and tectonic significance. In: B. Rosendahl (Editor), *Journal of African Earth Sciences Special Publication 8*, 2-4: pp. 283-306.

Karner, G. D. & Driscoll, N. W., 1999. Tectonic and stratigraphic development of the West African and eastern Brazilian Margins: insights from quantitative basin modelling. In: Cameron, N. R., Bate R.

H. & Clure, V. S., (Editors), The oil and gas habitats of the South Atlantic, Geol. Soc. London, Spec. Publ, 153: pp. 11-40.

Kusznir, N.J. & Karner, G. D., 2007. Continental lithospheric thinning and breakup in response to upwelling divergent mantle flow: application to the Woodlark, Newfoundland and Iberia margins, In: Karner, G. D., Manatschal, G. & Pinherio, L. M. (eds), Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup, Geological Society, London, Special Publications, 282, 389-419.

Labails, C., Olivet, J.-L., and the “Dakhla group”, 2009. Crustal Structure of the SW-Moroccan margin (Dakhla experiment). Part B - the tectonic heritage *Tectonophysics* (Special Issue: role of magmatism), 468: 83-97, [doi:10.1016/j.tecto.2008.08.028](https://doi.org/10.1016/j.tecto.2008.08.028).

Lavier, L. & Manatschal, G. 2006. A mechanism to thin the continental lithosphere at magma-poor margins, *Nature*, 440, 324-328. doi:10.1038/nature04608.

Lentini, M.R, Fraser, S. I. Scott Sumner, H. and Davies, R. J., 2010. Geodynamics of the central South Atlantic conjugate margins: implications for hydrocarbon potential. *Petroleum Geosciences*, 16: 217-229, doi: 10.1144/1354-079309-909.

Lucazeau, F., Leroy. S., Bonneville, A., Goutorbe, B., Rolandone, F., d'Acremont, E., Watremmer, L., Düşünür, D., Tuchais, P., Huchon, P., Bellahsen, N., & Al-Toubi, K., 2008. Persistent thermal activity at the Eastern Gulf of Aden after continental break-up. *Nature Geosciences*, 1: 854-858, doi:10.1038/ngeo359.

Lucazeau, F., Leroy, S., Rolandone, F., d'Acremont, E., Watremmer, L., Bonneville, A., Goutorbe, B. & Düşünür, D., 2010. Heat-flow and hydrothermal circulation at the ocean–continent transition of the eastern gulf of Aden. *Earth and Planetary Science Letters*, 295: 554–570.

Magnativa, L. P., 1992. Geometry and kinematics of the Reconcavo-Tucano-Jatoba Rift, NE Brazil, Ph.D. thesis, University of Oxford, 493 p.

Magnativa, L. P. & da Silva, H.T.F., 1995. The interplay Between Tectonics and Sedimentation in the Recôncavo Basin, Northeastern Brazil. *AAPG Bulletin*, 79, 11: 1590-1607.

Martinez, C. & Vargas, E., 1988. Sur les deformations synsédimentaires mésozoïques de la région de Macha - Pocoata - Colquechaca (nord de Potosi - Cordillère orientale de Bolivie). *Géodynamique*, 3, 1-2: 107-115.

Matias, L. M., Olivet, J.-L., Aslanian, D. & Fidalgo González, L., 2005. PLACA: A White Box for Plate Reconstruction and Best-Fit Pole Determination. *Computers and Geosciences*, 31, 437-452.

McKenzie, D., (1978). Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*. 40, 1: 25-32.

Moulin, M., D. Aslanian, J.-L. Olivet, I. Contrucci, L. Matias, L. Géli, F. Klingelhoefer, H. Nouzé, J.-P. Réhault and P. Unternehr, 2005. Geological constraints on the evolution of the Angolan margin based on reflection and refraction seismic data (ZaïAngo project), *Geophysical Journal*

79 *International*, v.162, 793-810.

80 Moulin, M., Aslanian, D., Olivet, J.-L. & P. Unternehr, Typologie des marges - 1ere Partie l'Atlantique
81 Sud, Rapport confidentiel, TOTAL, mai. 2006.

82 Moulin, M., Aslanian, D. & Unternehr, P., 2010, A new starting point for the South and Equatorial Atlantic
83 Ocean. *Earth Science Reviews*, 98, 1: 1-37, doi:10.1016/j.earscirev.2009.08.001.

84 Moulin, M. & Aslanian, D., 2010, Corrigendum to "A new starting point for the South and Equatorial
85 Atlantic Ocean" [Earth Science Reviews 98 (2010), 1–37], *Earth Science Reviews*, 103 : 197-198,
86 [doi:10.1016/j.earscirev.2010.10.001](https://doi.org/10.1016/j.earscirev.2010.10.001)

87 Mpodozis, C. and Ramos, V. A., 1990. The Andes of Chile and Argentina. In: G.E. Ericksen, M.T. Cafias
88 Pinochet and J.A. Reinemund (Editor), *Geology of the Andes and Its Relation to Hydrocarbon and*
89 *Mineral Resources. Earth Science Series*, 11. Circum-Pacific Council for Energy and Mineral
90 Resources, Houston, TX, pp. 59-90.

91 Ngako, V., Affaton, P., Nnange, J. M. & Njanko, Th., 2003. Pan-African tectonic evolution in central and
92 southern Cameroon: transpression and transtension during sinistral shear movements. *Journal of*
93 *African Earth Sciences*, 36: 207-214.

94 Olivet, J.-L. 1978. Un nouveau modèle d'évolution de l'Atlantique Nord Central. Thèse d'état, Univ. Paris
95 VII.

96 Nürnberg, D. & Müller, R. D. 1991. The tectonic evolution of the South Atlantic from Late Jurassic to
97 present. *Tectonophysics*, 191, 27-53.

98 Péron-Pinvidic, G. & Manatschal, G. 2009. The final riftng evolution at deep magma-poor passive margins
99 from Iberia-Newfounland: a new point of view. *Int. J. Earth Sci.* doi:10.1007/s00531-008-0337-9.

00 Pindell, J. & Dewey, J. F., 1982. Permo-triassic reconstruction of western pangea and the evolution of the
01 Gulf of Mexico/Caribbean region. *Tectonics*, 1, 2: 179-211.

02 Reston, T.J., 2010. The opening of the central segment of the South Atlantic: symmetry and the extension
03 discrepancy. *Petroleum Geosciences*, 16: 199-206, doi:10.1144/1354-079309-907.

04 Talwani, M., Ewing, J., Sheridan, R.E., Holbrook, W.S., Glover, L., 1995. The edge experiment and the
05 U.S. East Coast Magnetic Anomaly. In: Banda, E., *et al.* (Ed.), *Rifted Ocean-Continent Boundaries*.
06 Kluwer Academic, Netherlands, pp. 155–181.

07 Torsvik, T.H., Rousse, S., Labails, C., & Smethurst, M.A., 2009. A new scheme for the opening of the
08 South Atlantic Ocean and the dissection of an Aptian salt basin. *Geophysical Journal International*,
09 doi:10.1111/j.1365-246X.2009.04137.x

10 Torsvik, T.H., Rousse, S. & Smethurst, M.A., 2010. Reply to comment by D. Aslanian and M.Moulin on
11 'A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt
12 basin'. *Geophysical Journal International*, doi: 10.1111/j.1365-246X.2010.04728.x

13 Unternehr, P., Curie. D., Olivet, J.L., Goslin J. and Beuzart P. 1988. South Atlantic fits and intraplate

boundaries in Africa and South America. Mesozoic and Cenozoic Plate Reconstruction. *Tectonophysics*, 155, 169-179.

Unternehr, P., Péron-Pinvidic, G., Manatschal, G. & Sutra, E., 2010. Hyper-extended crust in the South Atlantic: in search of a model. *Petroleum Geosciences*, 16: 207-215, doi:10.1144/1354-079309-904.

Wernicke, B., (1985). Uniform sense normal simple shear of continental lithosphere. *Can. J. Earth Sci.*, 22: 108-125.

Wessel, P. and Smith, W. H. F., 1998. The Generic Mapping Tools: GMT

Zalán, P.V., Wolff, S., Conceição J.C.J. Astolfi, M.A.M., Vieira, I.S., Appi, V.T., Neto, E.V.S., Cerqueira, J.R., Marques, A., 1990. The Paraná Basin, Brazil. In: Leighton, M.W., Kolata, D.R., Oltz D.F. and Eidel, J.I. (Editors), Interior Cratonic Basins: *AAPG Memoir*, 51, 8, 81-708.

FIGURE CAPTIONS

Figure 1: Continental crust thinning process : conceptual versus kinematic approaches.

Top: Simplified geometries of a system of conjugate margins. Drawn after the conjugate Angola and Espírito Santo continental passive margins (Contrucci et al? 2004; Moulin et al., 2005 ; Aslanian et al., 2009; Unternehr et al., 2010). A) Conceptual approach (conservative model): The actual area of continental crust is intrinsically strictly equal to the initial area, the continental crust thinning process can be converted in the horizontal movement. B) Kinematic Constraints: the horizontal movement is given by precise kinematic reconstruction. A wide thinned basin remains in that case. The allochthonous domains (part 2) of each margin overlap each other and are not shown on figure B-2. The quantity of « missing » lower continental crust depends of the nature (lower continental or not) of the allochthonous domain.

Figure 2: Reconstitution of five systems of conjugate margins of the South Atlantic Ocean. Left : tightest initial reconstruction of Moulin *et al.* (2010) at LMA, ~133Ma (Gradstein *et al.*, 2004). The West African Plate is considered as the fixed plate. Dark blue lines represent the main structural constraints (Panafrican fault system, fracture zones). The hinge lines are drawn according to an industrial compilation (Unternehr, pers. comm.), Heilbron *et al.*, 2000, Karner & Driscoll, 1998; and industrial profiles (Moulin *et al.*, 2006). The magnetic anomalies “Large Marginal Anomalies” come from the interpretation of Moulin *et al.* (2010). In the central segment of the South Atlantic, a 280km wide gap persists between the two hinge lines. Mercator projection. Right: Five systems of conjugate margins: i) the Reconcavo-South Alagias-Jequitinhonha – South Gabon system, the Espírito Santo – Angolan system and the Santos – Namibe system in the central segment (Aslanian *et al.*, 2009) and ii) the Pelotas – Walvis system

48 and v) the Argentina – Orange system in the austral segment (this study). The « missing » low
49 continental crust domains are in red.

50

51 Figure 3: The pieces of the Jigsaw puzzle. The African plate is divided into four blocks. The South
52 America is divided into nine blocks. At LMA, ~133Ma (Gradstein *et al.*, 2004), before the rifting
53 phase, the Patagonia, Salado, Argentina, Rio Plata and Austral African sub-plates are fixed in
54 respect to each other, as the Guyana and West Africa subplates (see text for more explanations).

55

56 Figure 4: Case of Africa Plate deformation. This reconstruction is modified from the fit of Moulin
57 *et al.*, 2010, by a clockwise rotation of the Patagonia, Salado, Argentina, Rio Plata and Austral
58 African block, in order to reduce the remaining space between the two hinge lines at 150-160 km
59 in the Central segment of the South Atlantic Ocean (See table 1 for the Eulerian poles). The
60 deformations inferred by these additional motions are indicated within the red rectangles. See text
61 for explanations. Same legend as in Fig. 1. The West African Plate is considered as the fixed plate.
62 Mercator projection.

63

64 Figure 5: Case of Africa Plate deformation. This reconstruction is modified from the fit of Moulin
65 *et al.*, 2010, by counter-clockwise rotation of the São Francisco and Santos plates, to reduce the
66 remaining space between the two hinge lines at 150-160 km in the Central segment of the South
67 Atlantic Ocean (See table 2 for the Eulerian poles). The deformations inferred by this additional
68 motion are indicated in red. The deformations inferred by these additional motions are indicated
69 within the red rectangles. See text for explanations. Same legend as in Fig. 1. The West African
70 Plate is considered as the fixed plate. Mercator projection.

Aslanian & Moulin - Figure 1

Aslanian & Moulin -
Figure 2

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Aslanian & Moulin - Figure 3

79 Table 1. Finite Rotations for moving sub-plates compared to the Fit of Moulin et al., 2010 (with respect to the fixed West Africa
80 block) in the case of maximum intraplate deformation located in Africa. See Figure 4.
81

Chron	Pole of Rotation		Angle, deg	Source
	Latitude, deg	Longitude, deg		
Plata with respect to W. Africa				
LMA	53.90	-37.55	53.03	This study
Argentina with respect to W. Africa				
LMA	55.08	-38.61	53.12	This study
Salado with respect to W. Africa				
LMA	55.18	-39.17	52.61	This study
Austral with respect to W. Africa				
LMA	17.8	5.27	-4.5	This study

82 Table 2. Finite Rotations for moving sub-plates compared to the Fit of Moulin et al., 2010 (with respect to the fixed West Africa
83 block) in the case of maximum intraplate deformation located in South America. See Figure 5.
84
85

Chron	Pole of Rotation		Angle, deg	Source
	Latitude, deg	Longitude, deg		
São Francisco with respect to W. Africa				
LMA	51.77	-33.86	52.57	This study
Santos with respect to W. Africa				
LMA	50.32	-33.23	54.60	This study

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