Geophysical Journal International

Geophys. J. Int. (2010) **183,** 29–34 doi: 10.1111/j.1365-246X.2010.04728.x

Reply to comment by D. Aslanian and M. Moulin on 'A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin'

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Accepted 2010 July 7. Received 2010 July 7; in original form 2010 April 13

GJI Geodynamics and tectonics

SUMMARY

In their comment, Aslanian & Moulin argue that our model of South Atlantic opening is incompatible with several kinematic and geological constraints as recently evaluated in Moulin *et al.* They also claim that we have not appropriately referenced their work. We strongly disagree and in addressing their points will argue that our model is compatible with the most important constraints that have been assembled by the many scientists who have worked on the South Atlantic and that instead the interpretation by Moulin *et al.* suffers from serious flaws.

Key words: Palaeomagnetism applied to tectonics; Continental margins: divergent; Africa; South America.

1 INTRAPLATE DEFORMATION LIMITS

'In the African Plate, Torsvik *et al.* (fig. 1) used, without the correct references, the intraplate boundaries given by Moulin (2003), Moulin *et al.* (2005a, 2010), Aslanian *et al.* (2009), which follow the model of Guiraud & Maurin (1992).'

Incidentally, fig. 1 in Torsvik *et al.* (2009) does not show any intraplate boundaries and we did not use the boundaries given by Moulin and coworkers in 2003, 2005 nor did we have access to the most recent versions of these boundaries as used by Aslanian *et al.* (2009) (but not shown in this paper) or Moulin *et al.* (2010). How can they claim that we ignored their work when they were not published? Like our critics, we followed the model of Guiraud & Maurin (1992) with additions taken from Guiraud *et al.* (2005) and Basile *et al.* (2005) and we find it reassuring that we proposed broadly similar intraplate boundaries for Africa. In South America our interpretations of intraplate deformation boundaries differ, mostly because of the lack of reliable constraints. We will answer some of the comments below, although we concur with this quote from their comment:

'Both studies employ continental intraplate deformation in both South America and Africa Plates as suggested earlier by Curie (1984), Unternehr *et al.* (1988) and Nürnberg & Müller (1991). This deformation may be dispersed throughout large areas, diluted along several fault zones, but for geometrical purpose this deformation is represented in both articles by simple lines that must be regarded as symbolic.'

Just to exemplify that our critics do not follow their own philosophy, in remark 5 Aslanian & Moulin (2010) disagree with the boundary we draw through the General Levalle basin and argue that this basin cannot have accommodated 145 km of extension (Torsvik *et al.* 2009; fig. 5). However, as clearly discussed in our paper and references it is based on, there are several subparallel basins that were active between 150 and 126 Ma that could have accommodated the extension (Torsvik *et al.* 2009; fig. 8 and their appendix). On the other hand, we would argue that the 125 km of compression (Moulin *et al.* 2010) expected from the corner of the Bolivian orocline to the middle of the foreland basin of Bolivia and Brazil contradicts the geological evolution where the sedimentary fill is known to be coherent because the Palaeozoic and where a flexure of the Brazilian shield beneath the foreland is evident (Lyon-Caen *et al.* 1985). In addition, there is very little evidence of NW–SE compression reported for this time-window in the Andean part of South America and in the coastal areas (e.g. Jaillard 1994; Jaillard & Soler 1996; Ramos 2005).

2 KINEMATIC PROBLEMS AND CONSEQUENCES

When developing a 'self-consistent' model based on certain criteria, that particular model will inevitable differ in detail from any other models based on very different criteria. In the marine environs, the relative motions between tectonic plates are best determined by the matching of fracture zones and magnetic anomalies of the same age.

However, the South Atlantic went through a critical phase in its evolution during the Cretaceous Normal Superchron (CNS; 120.6–83.5 Ma) and the correct identification and age of pre-CNS magnetic anomalies claimed in the literature are at best uncertain; thus we are principally left with Euler poles determined from the fracture zone geometry and Euler angles that are estimated/interpolated or outright guessed from other geological/geophysical data. Thus, no quantitative criteria for goodness of fit or statistical uncertainties exist for the South Atlantic in contrast to the much better defined Central Atlantic opening story (Torsvik *et al.* 2008a, table 1). We and Moulin *et al.* (2010) and many others, invoke schematic intraplate boundaries in Africa and South America in order to obtain an opening story for the South Atlantic that makes geological 'sense'—but our efforts resemble a jigsaw puzzle where we don't know how many pieces (tectonic blocks) we need, how much displacement/extension/transtension took place along the boundaries and at what time these boundaries were active. These parameters differ in nearly all models.

Our South Atlantic model is based on realistic scenarios for intraplate deformation, pre-drift extension and seafloor spreading, which further serve as input for our global-scale reconstructions and geodynamics (Torsvik *et al.* 2010). There are no error-estimates in this model and we simply argue that the model is in reasonable agreement with the geological history of the region as well as palaeomagnetic data (not discussed; forthcoming paper). Critical constraining factors in our model include the location of continent–ocean boundaries (COBs), and the age and extent of salt basins. The COB is better described as a continental ocean transition (COT) zone between typical continental and oceanic crust, usually some tens of kilometres wide and perhaps as much as 50–100 km. Despite these limitations, establishing the location of the COB as a line on a large-scale map brings valuable insights into plate-reconstruction-derived estimates of pre-drift extension/lithospheric stretching and the location of the COB/COT is a first-order risk parameter in hydrocarbon exploration. Conversely, the model of Moulin *et al.* (2010) in the marine domain is not based on identifying and testing the COB by reconstructions but exclusively on the location of the hinge-line, that is, where the crust/lithosphere thickness is assumed to be 'normal' in their pre-rift positions. The hinge-line is commonly positioned near the shelf-break and is often associated with a pronounced-free air gravity anomaly. We assume (?) that Moulin *et al.* (2010) used seismic refraction and/or bathymetry/gravity (?) data to establish the hinge-line but we are not sure because the hinge-line on their map includes references to 'interpretation of Unternehr (personal communication, 2006)'. In any case, the hinge-line (as for the COB) is not an exact line for plate tectonic testing since passive margin stretching can be accompanied by interior continental extension.

Given all the above, when comparing non-quantitative models that are based on different assumptions and data sets and have no associated error estimates, it becomes preposterous to discuss models that differ by 50–100 km ($\sim$0.5–1° in equatorial regions). Remarks 1–10, 13, 15 and 17 mostly fall in this category. No detailed response is required to these remarks and differences which are essentially below the resolution of plate tectonic reconstructions, mostly based on postulations by other workers (see the extensive reference list in Aslanian & Moulin 2010). Below we therefore focus our response on valid and more interesting remarks.

3 REMARK 11

'The definition of their 'robust' continent–ocean boundary in the southern Santos Basin does not include the presence of the aborted oceanic ridge that is marked by a very large positive Bouguer anomaly just north of the Florianópolis Fracture Zone (FFZ), indenting the Aptian salt basin (Mohriak 2001; Gomes *et al.* 2002; Carminatti *et al.* 2008; Mohriak *et al.* 2008), neither the complicated kinematic history of the Santos Basin–Sao Paulo Plateau system (Aslanian *et al.* 2009; Moulin *et al.* 2010) and the probable presence of thickened oceanic crust in the southern São Paulo Plateau (Leyden *et al.* 1972, 1976; Cande *et al.* 1976, 1978; Kowsmann *et al.* 1977; Gondcalves 1991; Dermercian 1996; Karner 2000; Meisling *et al.* 2001; Mohriak 2001; Aslanian *et al.* 2009). All these misfits have strong consequences on the understanding of the mechanism of Passive Margin formation (Aslanian *et al.* 2009) and clearly show the need of precise and detailed kinematic reconstructions.'

Aslanian & Moulin (2010) claim that we did 'not include the presence of the aborted oceanic ridge that is marked by a very large positive Bouguer anomaly just north of the FFZ, indenting the Aptian salt basin'. As is clearly stated in our paper and further underlined by the question marks in our diagram (Fig. 1a) it is next to impossible to define the COB properly along the Santos Basin using gravity residuals. Based on (1) the assumption that salt deposition ended at 112 Ma (Aptian–Albian boundary); (2) that the Aptian salt basins where once conjugate basins that were not deposited on oceanic crust and (3) the well-defined COB on the African side, we have indicated the expected location of the COB based on our rotation model. A more complex model is hinted at in our manuscript and also shown in one of our earlier reconstructions (Fig. 1b, Torsvik *et al.* 2004), where we also indicate a possible aborted oceanic ridge. However, this is just speculation, not factual information and gravity anomalies in the Santos Basin could equally have resulted from younger hotspot-related volcanism, which we now favour. We therefore decided to make a simpler and more generalized model than our 2004 version. Fig. 1(b) shows, in essence, the main part of our South America story: (1) Early opening in the southernmost South Atlantic accommodated along the Parena–Etendeka-Fault Zone (PEFZ) and (2) lithospheric extension to the North of the PEFZ with eventual seafloor spreading at around 112 Ma. In fact our model show many similarities with the Moulin *et al.* (2010) model, including the introduction of a 112 Ma stage pole (all previous studies used linear interpolation between M0 and A30; 120.6–83.5 Ma). We are not aware of any other studies doing this guided by the shape and age of Aptian salt basins; we used this Aptian–Albian stage-pole in 2004 (Fig. 1b) and in Torsvik *et al.* (2008a, 2009). Moulin *et al.* (2010) has repeated our exercise (their pole differs by 1.8° in location and 0.9° in rotation angle), but there is no mention that we had already done this; the authors try to focus on differences and discrediting us, rather than the gross similarities between these models.

4 REMARK 12

'Using this data set without implying intraplate deformation in the Salado Basin seems not coherent to us. Furthermore, since 1997, a lot of further data were acquired and published (Max *et al.* 1999; Corner *et al.* 2002; Zalan & Oliveira 2005; the BGR data set). Using these data sets and some industrial magnetic maps, Moulin *et al.* (2010) re-interpreted the magnetic anomalies (see this article for details). Fig. 3 presents the kinematic reconstructions of Torsvik *et al.* with these new isochrons 'Large Magnetic Anomaly' (LMA), M4 and M0. The three reconstructions present large gaps and overlaps.'

Because we did not have access to industrial maps or the Moulin *et al.* (2010) reinterpretation of magnetic data we could naturally

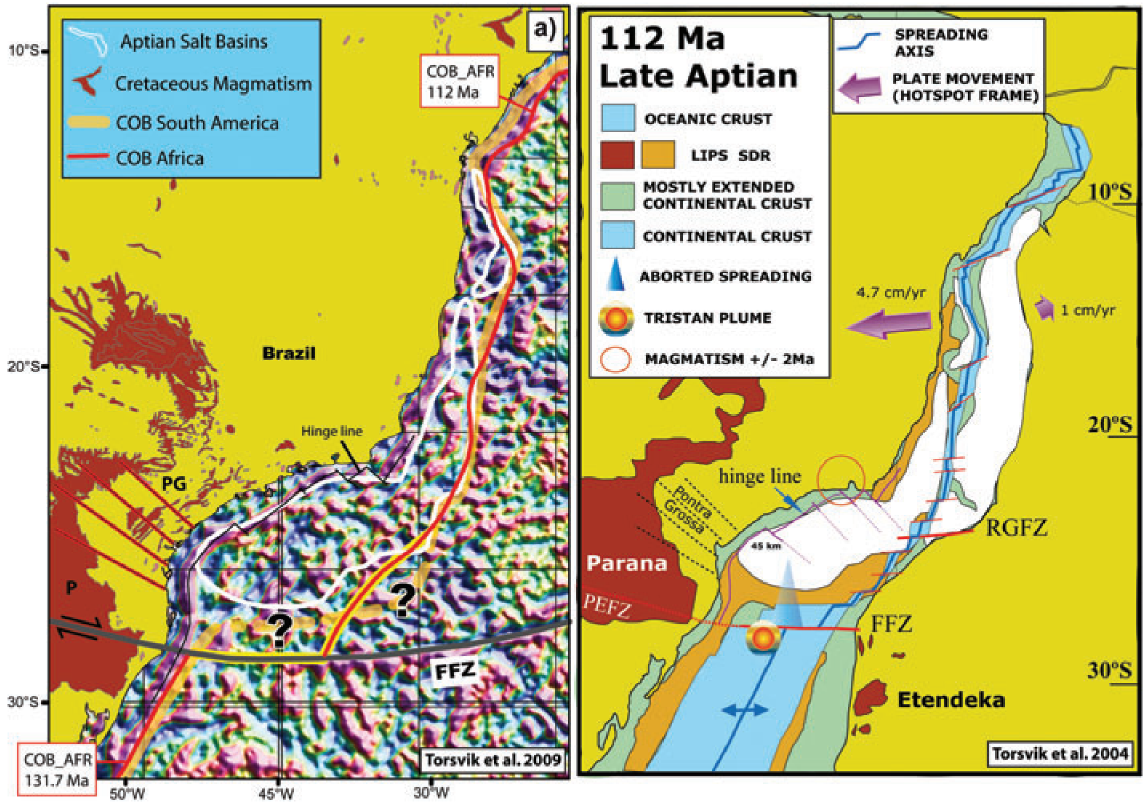

Figure 1. (a) Second vertical derivative of upward continued isostatic residual anomalies offshore Brazil along with continent–ocean boundary (COB) interpretations, Aptian salt outlines (white lines) and details in the faulted hinge-line (thin black line) on parts of the margin. Rotated COBs from the African margin (red lines) are also shown (112 Ma north of the FFZ and 131.7 south of the FFZ). COB interpretations along the Brazilian margin are thick orange transparent lines. The definition of the COB in the SW Santos basin is complex: originally, based on Torsvik *et al.* (2004), interpreted to follow the stippled orange line marked with question marks, but simplified in Torsvik *et al.* (2009) to match the conjugate African margin with a break-up age near the Aptian–Albian boundary (112 Ma). In Northern Santos and northwards and south of the FFZ, there is good match between the two conjugate COBs at 112 and 131.7 Ma, respectively. FFZ, Florianopolis Fracture Zone; PG, Ponta Gross dyke swarm; P, Parana. (b) Reconstruction of the Brazilian and Angolan margin at 112 Ma, that is, during the initial break-up and seafloor spreading north of the FFZ. This was shortly after salt deposition, which we argue once formed a single basin that was split in two after break-up. On this map (Torsvik *et al.* 2004) we indicated the location of a possible incipient spreading centre (later aborted) in the southernmost Santos Basin from 126–112 Ma.

not use these data and we can only make some brief comments. LMA is not an isochron: it is most likely related to seaward dipping reflectors (known for decades). Its age is unknown but the authors assume that all this magmatism is 133 Ma (arbitrarily coinciding with the main peak of the Parana–Etendeka event and thus suggesting southward rather than northward propagation in the southern segment or both?). Thus with a preconceived notion that break-up in the southernmost Atlantic took place at 133 Ma and using our reconstruction poles that assume mostly younger ages for breakup will inevitably lead to overlaps. Concerning the timing of the opening one should also be aware that we do not use the Gradstein *et al.* (2004) timesscale which will make all the M-anomalies too old; that implies that the Moulin *et al.* (2010) reconstructions are consistently older than ours. This was based on redefining M0 to 125 Ma, the appropriate age should be 120.6 Ma and the Gradstein *et al.* (2004) timescale is not recommended in the geomagnetic community (see e.g. Gee & Kent 2007; He *et al.* 2008). Concerning fig. 3 in Aslanian & Moulin (2010), their Chron M0 reconstruction and assuming that they used our 120.6 Ma and not 125 Ma (which is the age of their MO) the authors have developed a model that almost perfectly mimics ours. Mismatches of 25–60 km are below the resolution power of both studies and reflects the different methods and approaches.

5 REMARK 14

'Torsvik *et al.* (2009) end the South American intraplate deformation at chron M4. The main dominant pulse of Paraná–Etendeka is indeed dated between 135 and 130 Ma. Nevertheless, geochemical analyses show that the magmatic activity lasted until the Barremian/Aptian limit or Late Aptian, implying further intraplate deformation in this area.'

We are somewhat puzzled how geochemistry can reveal the age of magmatic activity and if so, do the authors advocate that magmatism must cause or only be related to large-scale faulting? Furthermore, we terminate movements on the PEFZ in South America at ∼126 Myr because there is practically no evidence that this fault actually exists in nature (also mentioned in Moulin *et al.* 2010). However, in order to allow seafloor spreading south of the FFZ we must invoke a 'diffuse' plate boundary here to only allow stretching north of FFZ. In our model, the PEFZ was active prior and during the eruption of the Parana–Etendeka large igneous province (PE LIP). PE was sourced from a deep plume but the eruption site did not mark precisely the site where the plume impinged the base of the lithosphere, but the location of a weakness zone in the lithosphere. If the PEFZ was active very long after the main PE LIP this should be seen in the geological record as massive offsets (which is not seen).

6 REMARK 16

'The second, south westwards movement given by the study of Torsvik *et al*. fails to describe exactly the Fracture Zones in the Equatorial Segment (white small circles; the pink small circles are given by Moulin *et al.* 2010, in comparison).'

This is a valid comment and was done deliberately to not break up South America into yet another plate. We have a very small mismatch between 100 and 83.5 Ma and then we have a perfect fit onwards using fracture zone geometries from Müller and coworkers. We note that Moulin *et al.* (2010) plot a few fracture zones based on a personal communication from Sandwell and Smith and thus

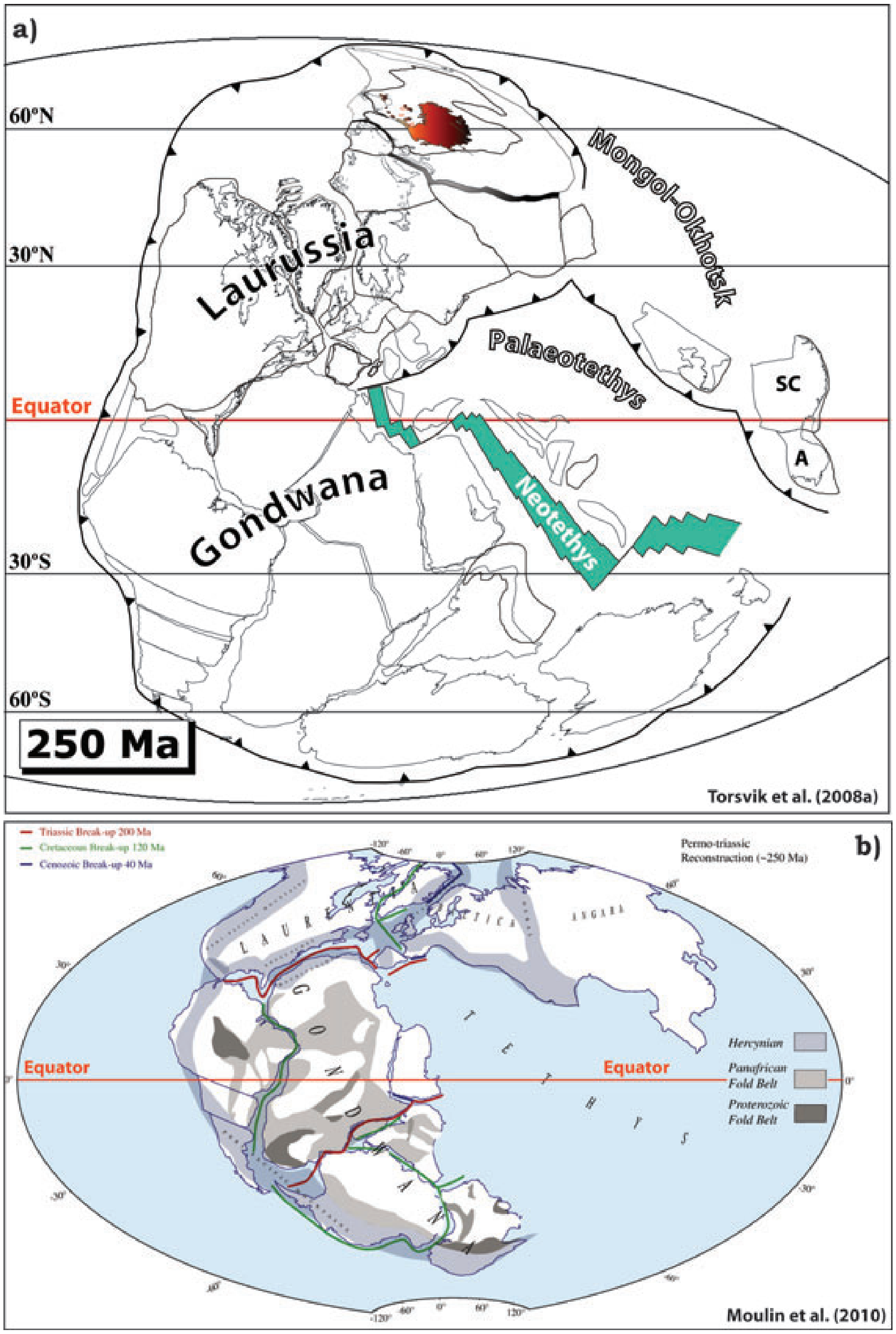

Figure 2. (a) Permo-Triassic (∼250 Ma) palaeomagnetic reconstruction of Torsvik *et al.* (2008a, fig. 19), at a time when Neotethys had opened and many peri-Gondwana terranes had separated from the Gondwana margin. Palaeotethyan and Mongol–Okhotsk oceanic lithosphere were being subducted beneath Eurasia and Siberia. Indochina (A), south China (SC) and north China (NC) were located in subtropical to equatorial latitudes in the eastern Palaeotethys and not part of Pangea. The Siberian Traps are shown in red shading in Siberia, but Siberia was not fully attached to Baltica and Kazakhstan at this time. Intracratonic boundaries in South America and Africa follows Torsvik *et al.* (2004) in this reconstruction. (b) Alternative reconstruction offered by Moulin *et al.* (2010). Note that the equator is misplaced ∼30° to the south, Hercynian and the much older Caledonian fold belts are considered the same, most Pangea breakup times are erroneous, their Pangea incorrectly includes most of Asia (including the China Blocks) and there is no Neotethys in their reconstruction.

we have no way of testing our model against their unpublished data.

7 CONCLUSION

In this reply we defend our work against criticisms made by Aslanian & Moulin (2010). Our model is mostly born out of an industry report from 2004 and publications from 2008 (Torsvik *et al.* 2004, 2008a, b) and was published before much of the material quoted by Aslanian & Moulin (2010).

We cannot resist making one single remark on one of their own diagrams, that is, fig. 1 in Moulin *et al.* (2010). The authors claim this and other figures 'constitutes the base canvas on which the problem of the continental margin genesis should be addressed'. However, their fig. 1 and the accompanying text suffer from several fundamental flaws. There is some debate about the geometry of Pangea at around 250 Ma (Pangea A versus Pangea B) but all scientists agree that the northern margin of Africa and South America was located near the equator (Fig. 2a). In their reconstruction, the equator is located 30° wrong (Fig. 2b). Their discussion confuses Hercynian and Caledonian Orogeny, which they argue 'formed by collision of Laurussia (they use the term Laurasia although not formed at this time) with Gondwana during the Permo-Triassic'. The Caledonian Orogeny actually happened at around 420–430 Ma during the formation of Laurussia (e.g. Norway colliding with Greenland) while the peak of the Hercynian Orogeny took place in the Late Carboniferous ($\sim$320 Ma). Practically all their indicated Pangea break-up lines are also erroneous, for example, 120 Ma break-up between Madagascar and India (should be 80–90 Ma) and 40 Ma break-up in the northeast Atlantic (should be $\sim$53–55 Ma). Clearly, this is not a good starting point to gain faith in their model.

ACKNOWLEDGMENTS

We thank Conall Mac Niocaill and Graeme Eagles as reviewers/moderators and Statoil for project funding.

REFERENCES

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 Trond H. Torsvik, Sonia Rousse, Cinthia Labails and Mark A. Smethurst, *Geophys. J. Int.*, in press, doi:10.1111/j.1365-246X.2010.04727.x. (this issue).

Aslanian, D. *et al*., 2009. Brazilian and African passive margins of the central segment of the South Atlantic Ocean: kinematic constraints, *Tectonophysics,* **468,** 98–112.

Basile, C., Mascle, J. & Guiraud, R., 2005. Phanerozoic geological evolution of the Equatorial Atlantic domain, *J. Afr. Earth Sci.,* **43,** 275–282.

Carminatti, M., Wolff, B. & Gamboa, L.A.P., 2008. New exploratory frontiers in Brazil, in *Proceedings of the 19th World Petroleum Congress*, Expanded Abstracts CD, 11.

Corner, B., Cartwright, J. & Swart, R., 2002. Volcanic passive margin of Namibia: a potential fields perspective, *Geol. Soc. Am. Special Papers*, **362**, 203–220, doi:10.1130/0-8137-2362-0.203.

Curie, D., 1984. *Ouverture de l'Atlantique Sud et Discontinuités Intra-Plaque: Une Nouvelle Analyse*, Univ. de Bretagne Occidentale, Brest, p. 192.

Demercian, L.S., 1996. A halocinese na evolução do Sul da Bacia de Santos do Aptiano ao Cretáceo Superior, *MS thesis*. Universidade Federal do Rio Grande do Sul, Porto Alegre, Brazil, p. 201.

Gee, J.S. & Kent, D.V., 2007. Source of Oceanic magnetic anomalies and the geomagnetic polarity timescale, *Treatise Geophys.,* **5,** 455–507.

Gomes, P.O., Parry, J. & Martins, W., 2002. The outer high of the Santos Basin, Southern Paulo Plateau, Brazil: Tectonic setting, relation to volcanic events and some comments on hydrocarbon potential, *AAPG Hedberg Conference 'Hydrocarbon Habitat of Volcanic Rifted Passive Margins'*, Stavanger, Norway, 2002 September 8–11, Am. Assoc. Petrol. Geologists, Tulsa, OK.

Gonçalves de Souza, K., 1991. La marge continentale brésilienne sudorientale et les domaines océaniques adjacents: structure et evolution, *PhD thesis*, University Pierre et Marie Curie, Paris, p. 230.

Gradstein, F.M., Ogg, J.G., Smith, A.G., Bleeker, W. & Lourens, L.J., 2004. A new geological timescale with special reference to Precambrian and Neogene, *Episodes,* **27,** 83–100.

Guiraud, R. & Maurin, J.C., 1992. Early cretaceous rifts of Western and Central Africa. An overview, *Tectonophysics,* **213,** 153–168.

Guiraud, R., Bosworth, W., Thierry, J. & Delplanque, A., 2005. Phanerozoic geological evolution of Northern and Central Africa: an overview, *J. Afr. Earth Sci.,* **43,** 83–143.

He, H., Pan, Y., Tauxe, L., Qin, H. & Zhu, R., 2008. Toward age determination of the M0r (Barremian-Aptian boundary) of the Early Cretaceous, *Phys. Earth planet. Int.,* **169,** 41–48.

Jaillard, E., 1994. Kimmeridgian to Paleocene tectonic and geodynamic evolution of the Peruvian (and Ecuadorian) margin, in *Cretaceous Tectonics in the Andes,* pp. 101–167, ed. Salfity, J.A., Vieweg & Sohn, Braunschweig-Wiesbaden.

Jaillard E. & Soler P., 1996. Cretaceous to early Paleogene tectonic evolution of the northern Central Andes (0–18 degrees S) and its relations to geodynamics, *Tectonophysics,* **259,** 41–53.

Karner, G.D., 2000. Rifts of the Campos and Santos Basins, Southeastern Brazil: distribution and Timing, in *Petroleum systems of South Atlantic margins*, AAPG Memoir 73, pp. 301–315, eds Mello, M.R. & Katz, B.J., Am. Assoc. Petrol. Geologists, Tulsa, OK.

Kowsmann, R., Leyden, R. & Francisconi, O., 1977. Marine seismic investigations, Southern Brazil margin, *Am. Assoc. Petrol. Geol. Bull.*, **61**, 546–557.

Leyden, R., Bryan, G. & Ewing, M., 1972. Geophysical reconnaissance on African shelf: 2. Margin sediments from Gulf of Guinea to Walvis Ridge, *Am. Assoc. Petrol. Geol. Bull.*, **56**, 682–693.

Leyden, R., Asmus, H., Zembruscki, S. & Bryan, G., 1976. South Atlantic diapiric structures, *Am. Assoc. Petrol. Geol. Bull.*, **60**, 196–212.

Lyon-Caen, H., Molnar, P. & Suarez, G., 1985. Gravity anomalies and flexure of the Brazilian shield beneath the Bolivian Andes, *Earth planet. Sci. Lett.,* **75,** 81–92.

Max, M.D., Ghidella, M., Kovacs, L., Paterlini, M. & Valladares, J.A., 1999. Geology of the Argentine continental shelf and margin from aeromagnetic survey, *Mar. Pet. Geol.*, **16**, 41–64.

Meisling, K.E., Cobbold, P.R. & Mount, V.S., 2001. Segmentation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil, *Am. Assoc. Petrol. Geol. Bull.*, **85**(11), 1903–1924.

Mohriak, W.U., 2001. Salt tectonics, volcanic centers, fracture zones and their relationship with the origin and evolution of the South Atlantic Ocean: geophysical evidence in the Brazilian and West African margins, in *Proceedings of the 7th International Congress of The Brazilian Geophysical Society*, p. 1594, Salvador da Bahia, Brazil, 2001 October 28–31.

Mohriak, W.U., Nemcok, M. & Enciso, G., 2008. South Atlantic divergent margin evolution: rift-border uplift and salt tectonics in the basins of SE Brazil, in *West Gondwana pre-Cenozoic Correlations Across the South Atlantic Region*, Geol. Soc. Spec. Pub. Vol. 294, pp. 365–398, eds Pankhurst, R.J., Trouw, R.A.J., Brito Neves, B.B. & de Wit, M.J., Geological Society, London.

Moulin, M., 2003. Etude géologique et géophysique des marges continentals passives: exemple du Zaïre et de l'Angola, *PhD thesis*, Univ. de Bretagne Occidentale, Brest, p. 360, http://www.ifremer.fr/docelec/doc/2003/these-82.pdf.

Moulin, M., Aslanian, D., Olivet, J.-L., Matias, L., Labails, C., Rabineau, M. & Unternehr, P., 2005a. A New Starting point for the History of South and Equatorial Atlantic Oceans, *EOS, Trans. Am. geophys. Un.*, **86**(18) Jt. Assem. Suppl., Abstract T53A-02, http://wwz.ifremer.fr/drogm/mediatisation/posters/geodynamique.

Moulin, M., Aslanian, D. & Unternher, P., 2010. A new starting point for the South and Equatorial Atlantic Ocean, *Earth-Sci. Rev.,* **98,** 1–37.

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

Ramos, V. A, 2005. Argentina, in *Encyclopedia of Geology,* Vol. 1, pp. 153–163, eds Selley, R.C., Cocks, L.R.M. & Plimer, I.R., Elsevier Academic Press, Oxford, United Kingdom.

Torsvik, T.H., Eide, E.A., Redfield, T.F., Lundin, E., Smethurst, M.A. & Ebbing, J., 2004. South Atlantic reconstructions: a self-consistent model. NGU Report 2004.024, p. 100. Available at: http://www.geodynamics.no/guest/NGU_Report_2004_024.pdf

Torsvik, T.H., Müller, R.D., Van Der Voo, R., Steinberger, B. & Gaina, C., 2008a. Global plate motion frames: toward a unified model, *Rev. Geophys.,* **46,** RG3004, doi:10.1029/2007RG000227.

Torsvik, T.H., Gaina, C. & Redfield, T.F. 2008b. Antarctica and global paleogeography: from Rodinia, through Gondwanaland and Pangea, to the birth of the Southern Ocean and the opening of gateways, in *Antarctica: A Keystone In a Changing World—Proc. 10th International Symposium on Antarctic Earth Sciences*, pp. 125–140, eds Cooper, A.K., Barrett, P.J., Stagg, H., Storey, B., Stump, E., Wise, W. & the 10th ISAES editorial team, The National Academies Press, Washington, DC.

Torsvik, T.H., Rousse, S., Labails, C. & Smethurst, M.A., 2009. A new scheme for the opening of the South Atlantic Ocean and dissection of an Aptian Salt Basin, *Geophys. J. Int.,* **177,** 1315–1333.

Torsvik, T.H., Steinberger, B., Gurnis, M. & Gaina, C., 2010. Plate tectonics and net lithosphere rotation of the past 150 Myr, *Earth planet. Sci. Lett.,* **291,** 106–112.

Unternher, P., Curie, D., Olivet, J.L., Goslin, J. & Beuzart, P., 1988. South Atlantic fits and intraplate boundaries in Africa and South America. Mesozoic and Cenozoic Plate Reconstruction, *Tectonophysics*, **155**, 169–179.

Zalán, P.V. & Warme, J.E., 1985. Tectonics and sedimentation of the Piaui-Camocim sub-basin, Ceara Basin, offshore Northeastern Brazil. *Ciência-Têcnica-Petróleo, Exploração de Petróleo*, **17**, 71.