Geophysical Journal International
October 2010, Volume 183, Issue 1, Pages 20–28
http://dx.doi.org/10.1111/j.1365-246X.2010.04727.x

The definitive version is available at http://onlinelibrary.wiley.com/

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

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Abstract:

Torsvik *et al.* recently presented a revised model for the opening of the South Atlantic Ocean. According to these authors, this new plate tectonic model is internally consistent and consistent with globally balanced plate motion solutions and takes into account realistic intraplate deformation. However, this model shows a number of kinematic and geological problems that we underline here, together with some comparisons with the new kinematic model recently proposed by Moulin *et al.*

Keywords: Plate motions; Continental margins: divergent; Africa; Atlantic Ocean; South America

Two papers were submitted and published recently on the same topic: "The new starting point for the South Atlantic Ocean" by Moulin, Aslanian & Unternher (Earth Science Reviews, submitted August 2008, 2009) and "A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin" by Torsvik, Rousse, Labails & Smethurst (Journal Geophysical International, submitted October 2008, 2009). The two scientific approaches as well as their results are quite different. The Moulin et al. paper proposes, after a critical review of the latest published kinematic models, a new evolution of the whole Equatorial and South Atlantic Ocean based on new interpretation of magnetic anomalies, seafloor isochrons, flow lines, fracture zones, continental and oceanic homologous structures and radiometric ages of igneous rocks, from the tightest reconstruction (Hauterivian) to Chron C34 (Campanian). The Torsvik et al. paper considers the Aptian salt accumulation and their new COB location of the Central segment of the South Atlantic Ocean in a new kinematic framework and evolution centred on the kinematic fit of the central segment of the South Atlantic published by Nürnberg & Müller in 1991. We present here a detailed analysis of the Torsvik *et al.* model, which presents a number of kinematic and geological problems.

Intraplate deformation limits

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 purposes this deformation is represented in both articles by simple lines that must be regarded as symbolic.

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). Nevertheless, they do not separate the Benue microplate from the South Africa sub-plate.

In South America plate, some differences are notable: the Tucano block described by Szatmari *et al., (*1985), Milani & Davison (1988) and Szatmari & Milani (1999) is missing in Torsvik *et al.* model. More importantly, the Transbrasiliano lineament, one of the major intraplate active features (Sykes, 1978), does not play any role in their reconstruction. Furthermore and strangely enough, contrary to Nürnberg & Müller (1991), they do not use the Salado and Punta del Este Basins as an intraplate boundary while they do use the Colorado Basin in this way. This point has a strong importance in the reconstruction of the Southern Segment as we will show later. Lastly, they do not separate the Santos microplate from the rest of the Amazonian sub-plate, which also has strong importance in the genesis of the Santos Basin – Sao Paulo Plateau system (Moulin *et al.,* 2010).

Kinematic problems and consequences

1- General view

Figure 1 shows a general view of the main problems presented by the fit given by Torsvik *et al.*

(1) In the Equatorial segment, there is an overlap of more than 100km of the Precambrian Ilha de Santana Platform on the West African craton. (2) Eastwards, the overlap of the Brazilian coast and the Benue coast is more than 280km and the extension in the Benue area of more

than 130km is far larger than the amount given by previous authors: 85 km for Fairhead (1988), between 10 and 50 km for Unternehr *et al.*, (1988) and between 60 and 70 km, with 20 to 30 km of sinistral strike-slip movement, for Nürnberg & Müller (1991). (3) In the area of Amguid-Gassi Touil-Algéria and 10°N lineaments, the Torsvik *et al.* model shows an overlap about 25-80km which implies an extension with no strike-slip movement, while the geological data indicate a transpressive deformation (Boudjema, 1987, in Guiraud & Maurin, 1992). (4) In the Tenere Basin, the extension is twice that expected by Fairhead (1988). (5) At last, in South America, this model shows also an extension of about 145km in the 50km wide General Levalle Basin (Webster *et al.*, 2004).

2- **The Central Segment**

Following Unternehr *et al.* (1988) suggestions, Nürnberg & Müller (1991) presented one of the first reconstruction including both African and South American intraplate deformation. Nevertheless, this reconstruction presents a number of important misfits, already discussed in a previous paper (Aslanian *et al.*, 2009). The model of Torsvik *et al.*, which uses the poles of Nürnberg & Müller (1991) between the Amazonia and the South Africa plates before the Aptian time, reproduces therefore some of those misfits. Figure 2 summarizes this discussion and the consequences of their reconstruction and compares it with our kinematic reconstruction. The Torsvik et al reconstruction shows: (6) a significant overlap in Niger Delta (more than 280km), previously quoted, which will be difficult to explain even with a high rate of sedimentation and delta progradation (less than 150km from Eocene to present day coast, Heino & Davies, 2007); (7) a misfit of the conjugate lineaments of Sanaga/Ngaoundere and Pernambuco/Patos lineaments; (8) an overlap of the hinge line of more than 50 km (that is an overlap of the conjugate unthinned margins) in the northern part of the central area (dark green area); (9) a small dextral movement in the Paraná area, while Eyles and Eyles (1993) quoted a 150km dextral movement, and a large extension of about 125km never observed. (10) Torsvik *et al.* (2009) assume intraplate deformation to position the Aptian salt basins side by side before breakup but stop the salt south of Salvador, in Brazil. However, there is evidence that the salt basin continues up to the Sergipe-Alagoas Basin (Mohriak, 2003; Mohriak & Rosendalh 2003); (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, indenting the Aptian salt basin (Mohriak, 2001; Gomes *et al.*, 2002; Mohriak *et al.*, 2008; Carminatti *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; Mohriak 2001; Meisling *et al.*, 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.

3- The Austral Segment

In the Southern segment, Torsvik *et al.* (2009) used the magnetic data set of Müller *et al.* (1997). This data set is a world digital grid with a 6 arc min interval, where each grid node was determined by linear interpolation between adjacent isochron in the direction of the spreading. This grid was built using the plate reconstruction poles, especially those from Nürnberg & Müller (1991) who located an intraplate boundary in the Salado Basin. (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). Figure 3 presents the kinematic reconstructions of Torsvik *et al.* with these new isochrons LMA, M4 and M0. The three reconstructions present large gaps and overlaps. (13) In particular for LMA and M4 reconstructions, the northern part of the Southern Segment (north to the Salado Basin) presents up to 70km-large gaps while the southern part has up to 200km-large overlaps. These observations show the importance of the deformation in the Salado basin, which must play the same role as in the Colorado Basin and divide the Paranà sub-plate in two parts, as suggested previously by Nürnberg and Müller (1991).

(14) Finally , Torsvik *et al.*, (2009) end the South American intraplate deformation at chron M4. The main dominant pulse of Paraná-Etendeka is indeed dated between 135Ma and 130 Ma (Milner *et al.*, 1992; 1995; Peate *et al.*, 1992; Renne *et al.*, 1992; Turner *et al.*, 1994). Nevertheless, geochemical analyses show that the magmatic activity lasted until the Barremian/Aptian limit or Late Aptian (Lustrino *et al.*, 2005, cited Renne *et al.*, 1992, 1996;

Turner *et al.*, 1994; Stewart *et al.*, 1996; Schmitt *et al.*, 2000; Tello Saenz *et al.*, 2003; Frindt *et al.*, 2004; Guedes *et al.*, 2005), implying further intraplate deformation in this area.

4- The Equatorial Segment

Figure 4A presents a zoom of both reconstructions. Both reconstructions fit the conjugate Guinean and Demerara Plateaux. Nevertheless, the overlap of the Precambrian Ilha de Santana Platform on the West African craton in the Torsvik *et al.* model is more than 100km (1) and could not be explained by the very limited extension observed in the main sedimentary Jurassic-Cretaceous basins (San Luis, Grajau, deep Ivorian Basins...). This overlap decreases (about 50km) but continues eastwards until the Benue area. (15) This position implies a rift evolution in two phases, never described in field studies (Zalan & Warme, 1985; Conceição *et al.*, 1988; Matos, 2000; Basile *et al.*, 2005), with a first SSE movement of the South America plate (Fig 4B) while Moulin *et al.* (2010) describe the movement from the fit to the Chron C34, with a single Eulerian pole. Fig 4C presents the reconstruction at Chron C34 of the equatorial segment given by Nürnberg & Müller (1991) with its well-marked fractures zones, from the ridge to the margins, which are the imprint of the relative movement between the two plates, and shows that (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). (17) Lastly, the authors propose a connection with the Central Atlantic by a seafloor spreading propagation north of the Niger delta at the mid-Albian times (around ~100 Ma) which seems inconsistent with the Late Aptian/ Early Albian age (112 Ma) of the unconformity defined on various sedimentary basins in the Equatorial segment (Pontes & Asmus, (1976); Szatmari *et al.* (1987); Gouyet (1988), Blarez (1986), Matos (2000); Mohriak (2003) & Zalan (2004), Basile *et al.*, (2005).

Some of those 17 points can be discussed as they depend on interpretations that could be debated but some others are based on consensus interpretations of features and their significance and the whole list disqualifies the Torsvik and co-authors model.

New plate tectonic models need indeed to be internally consistent. However, this is not the single condition and all new and old geological and geophysical data have to be considered. This task implies playing between very detailed studies and global synthesis. A global balanced plate motion solution could therefore be based on problematic regional plate tectonic models.

The huge task of kinematic studies is to try to invalidate the proposed model for every new data in order to test its robustness. It is therefore normal that this kind of study progresses step by step.

Acknowledgements:

The GMT software (Wessel & Smith, 1995) package and the PLACA software (Matias *et al.*, 2005, http://www.ifremer.fr/drogm/telechargement/placa_version_0_1.) were used in the preparation of this paper. We thank Marina Rabineau and Alison Chalm for their language corrections. M. Moulin is sponsored by LATTEX/IDL grant - ISLF-5-32 co-financed by FEDER. We thank Conall MacNiocaill and two others anonymous reviewers for their useful comments.

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Figure Caption;

Figure 1: Pre-drift reconstruction of Torsvik *et al.* (2009) at 180 Ma (Early Jurrasic). The West Africa block is considered as the fixed plate. Overlaps between the hinge lines are in dark green, gaps in light green. Following Curie (1984), Unternehr *et al.* (1988) and Nürnberg & Müller (1991), these authors proposed a model with 5 sub-plates in Africa and 4 sub-plates in South American. This model shows important overlaps, gaps and offsets, in the Equatorial segment (the platform Ilha de Santana on the West African craton), in the northern part of the Central Segment and in the Southern Segment (see text for details). Cratons are represented by brown lines (after Trompette, 1994). Sedimentary Cretaceous basins are represented by green lines (after Choubert *et al.*, 1968; Almeida *et al.*, 1970; Urien & Zambrano, 1973; Hinz *et al.*, 1999; Turner *et al.*, 1994; Trompette, 1994). The main structural constraints (lineaments and plateau limits) used for the kinematic reconstructions (blue lines) are drawn according to Gouyet (1988), Choubert *et al.* (1968), Gueguen (1995), Almeida *et al.* (1970) and Curie (1984). Cretaceous volcanism (in red) and triassic volcanism (in purple) limits are by Almeida *et al.* (1970,) Jacques (2003a; 2003b), Turner *et al.* (1994), Araujo *et al.* (2000), Marzoli *et al.* (1999a) and Choubert *et al.* (1968). Hinge lines (thick red lines) are based on the compilation of the interpretation of Unternehr (comm. pers.), Heilbron *et al.* (2000), Karner & Driscoll (1999) and Moulin *et al.* (2006). The "Large Magnetic Anomalies" are based on a new interpretation of Moulin *et al.*, 2009. Mercator projection.

Figure 2: Comparison of the two initial reconstructions in the Central Segment of the South Atlantic Ocean. West Africa is fixed. In the Equatorial and Central Segments, blue lines represent the Panafrican fault systems (Ngaoundéré-Sanaga, Patos-Pernambuco and Kandi-Sobral lineaments: Black & Girod, 1970; Dumont, 1986, De Almeida *et al.*, 1970, Guiraud & Alidou, 1981). The hinge lines are drawn according to an industrial compilation (Unternehr, comm. pers.), Heilbron *et al.* (2000), Karner & Driscoll (1999) and industrial profiles (Moulin *et al.*, 2006). Aptian salt extension (pink areas) are based on a compilation of different sources (Pautot *et al.*, 1973; Renard & Mascle, 1974; Emery *et al.*, 1975; Lehner & De Ruiter, 1977; Rosendahl *et al.*, 1991; Rosendahl & Groschel-Becker, 1999; Meyers *et al.*, 1996; Marton *et al.*, 2000; Contrucci *et al.*, 2004; Moulin *et al.*, 2005b for the African side, and Butler, 1970; Mascle & Renard, 1976; Leyden *et al.*, 1976 *in* Curie, 1984; Heilbron *et al.*, 2000; Unternehr,. pers. comm.. for the Brazilian side). The dark green areas represent the overlap, while the light green represent the gap between the 2 hinge lines. 1) the right side presents the reconstruction of Torsvik *et al.* (2009) following the Eulerian pole of Nürnberg & Müller (1991) between Amazonia and South Africa. They improve the position of the conjugate plateaus (Demerara/Guinea) and lineaments (Kandi/Sobral) with a modification of the African intraplate deformation. As already quoted by Aslanian *et al.* 2009, the hinge lines overlap by more than 90 km in this area. 2) the left side presents the reconstruction from Moulin *et al.*, (2009). In the Central segment, this model shows a gap of 280 km between the two hinge lines (See Aslanian *et al.*, 2009 for explanations).

Figure 3: Three kinematic reconstructions from the Early Jurrasic (180 Ma – pre-drift reconstruction) to the Barremian/Aptian Boundary (M0) of the Torsvik *et al.* model, using the new isochrons defined by Moulin *et al.*, 2009 (for detail, see their paper). West Africa is fixed and not showed on the figure. The three reconstructions present large gaps and overlaps, in particular at LMA and M4 times. The northern part of the Southern Segment (north to the Salado Basin) presents up to 70km-large gaps while the southern part has up to 200km-large overlaps. These observations show the importance of the deformation in the Salado basin, which must play the same role than the Colorado Basin and divide the Paranà sub-plate in two parts, as suggested previously by Nürnberg and Müller (1991). Same legend as in Figure 1. Oblique Mercator Projection. See Torsvik *et al.* (2009) for the Eulerian poles used in this figure.

Figure 4: A) Comparison of the two initial reconstructions in the Equatorial Segment. The red line represents the African High Gravity Anomaly, whereas the green line represents the South American

High Gravity Anomaly. The blue lines represent the Panafrican fault systems (Ngaoundéré-Sanaga, Patos-Pernambuco and Kandi-Sobral lineaments: Black & Girod, 1970; Dumont, 1986, De Almeida *et al.*, 1970, Guiraud & Alidou, 1981). The grey areas represent the overlap between the 2 High Gravity Anomalies. 1) The right side shows the reconstruction of Torsvik *et al.* (2009): they improve the position of the conjugate plateaus (Demerara/Guinea) and lineaments (Kandi/Sobral) in comparison of Nürnberg and Müller's model. Nevertheless this new position implies a too tight reconstruction and large intraplate deformation in the Benue Trough. 2) On the left side is the reconstruction from Moulin *et al.*, (2009). This model takes into account a large amount of geological observations and presents the Equatorial segment as an "incompressible zone". They describe the movement from the fit to the Chron C34, with a single Eulerian pole

B) Kinematic evolution of the South America plate in respect to the West Africa plate, for the Torsvik *et al.* model (2009), from the fit to the Chron C34. This model implies an evolution in two phases with a first SSE movement (from M4 and M0: red small circle) of the South America plate and a second NNE-SSW tranding mouvement (from M0 to Chron C34; orange, and grey small circles).

C) Kinematic reconstruction at Chron 34 (84Ma) with gravity data from Sandwell & Smith (1997) of the Equatorial Atlantic Ocean after Nürnberg and Müller (1991). Note the well-marked fractures zones, from the ridge to the margins. The Africa Plate and its attached gravity grid are fixed; the South American plate and gravity grid have been rotated with the Eulerian pole from Nürnberg and Müller (1991). The heavy red line represents the accreting ridge at that time. The black dotted lines represent the small circles (relative movement between the Africa and America plates) calculated with the intermediate pole between C34 and 112 Ma (Torsvik *et al.*, 2009), whereas the white dotted lines represent the small circles calculated with the intermediate pole between C34 and 112 Ma (Moulin *et al.*, 2009). The westwards movement given by the study of Torsvik et al fails to describe precisely the Fracture Zones in the Equatorial Segment. Same geological structure legends as in Figure 1. Mercator projection. See respective papers for the Eulerian poles used in this figure.

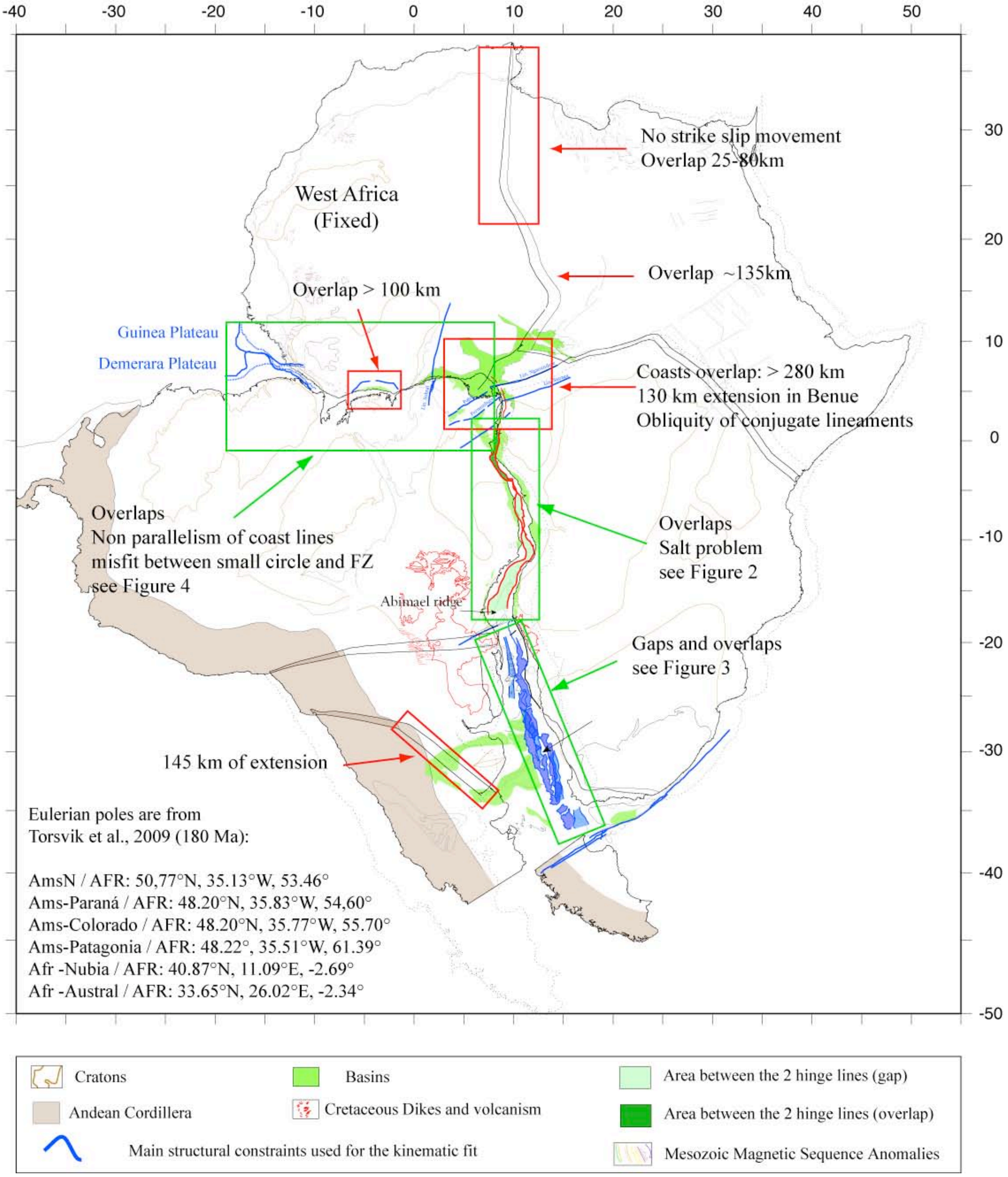

Figure 1 – Aslanian & Moulin

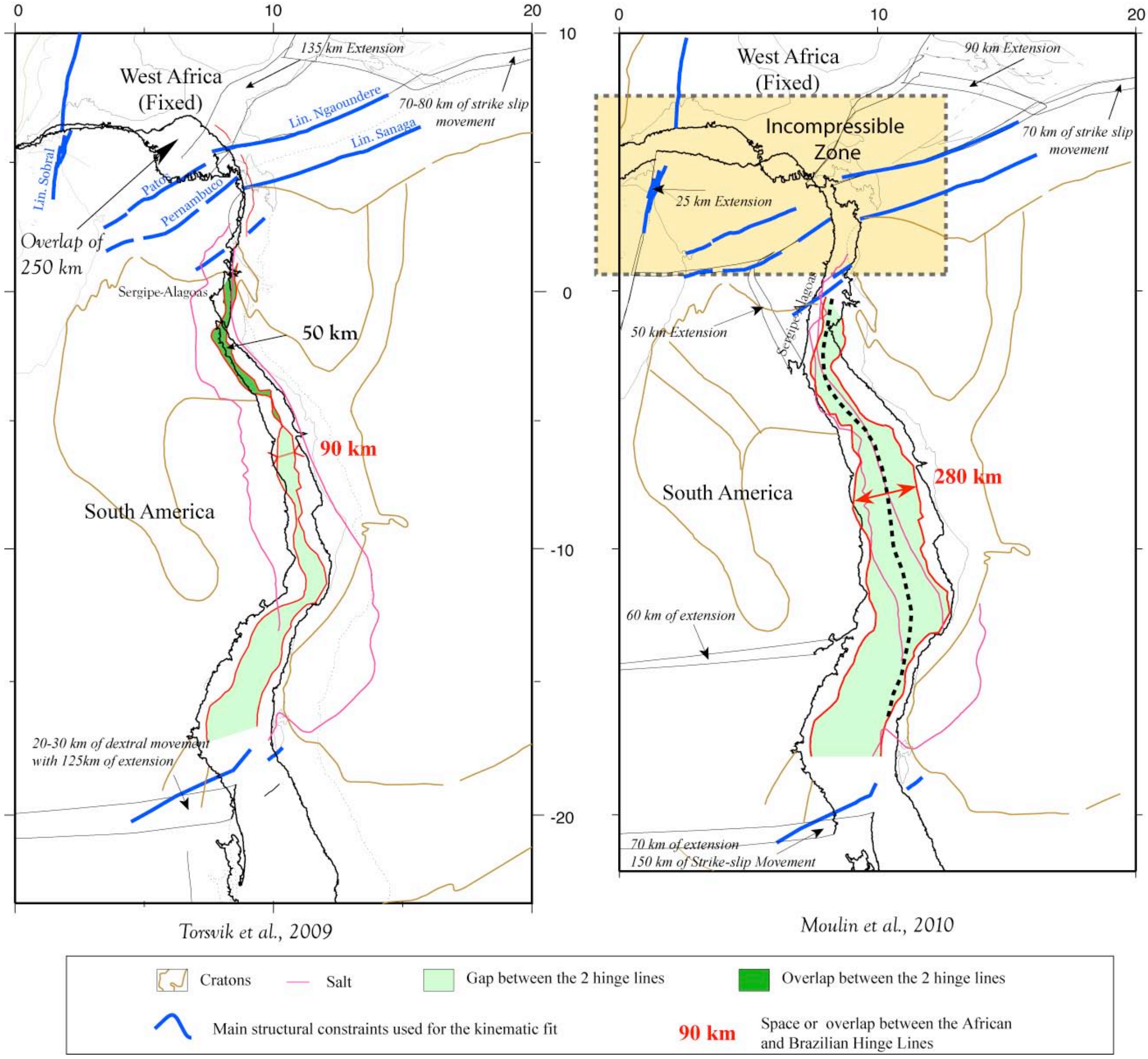

Figure 2- Aslanian & Moulin

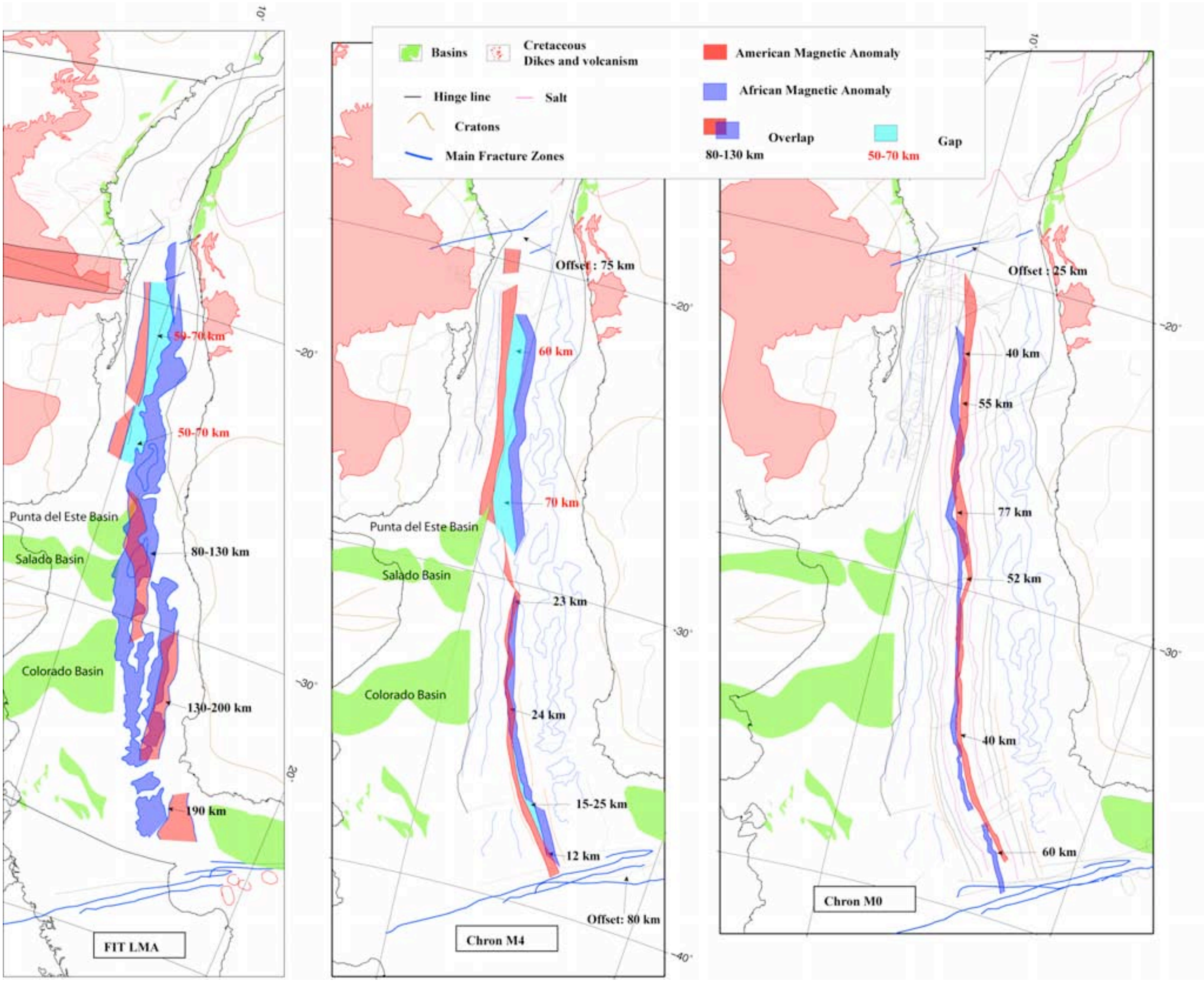

Figure 3 - Aslanian & Moulin

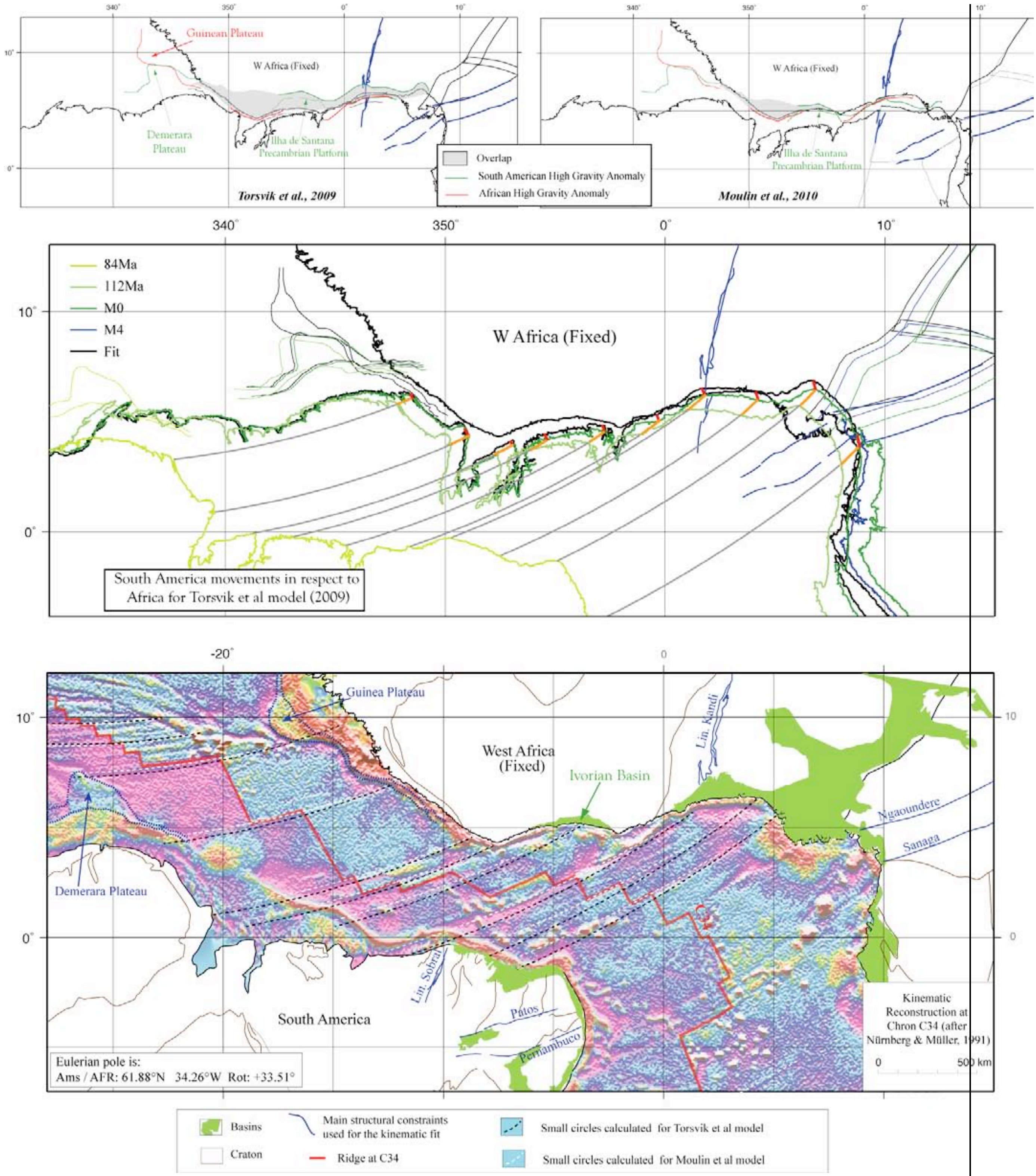

Figure 4 Aslanian & Moulin