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New starting point for the Indian Ocean: Second phase of breakup for Gondwana

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Abstract :

The amalgamation of Gondwana and its subsequent fragmentation has been a subject of several studies over the past five decades, yet the very important question of the initial geometry of the supercontinent remains enigmatic. Current reconstruction models of the Indian Ocean are characterized by large gaps, overlaps and misfits of major structural and Cratonic bodies in their fit, and positions of tectonic blocks that are inconsistent with field observations, a phenomenon sustained by inadequate data, long standing debates and a lack of consensus on the nature of major structures and basins in the ocean. Past attempts to reconstruct the initial fit of the ocean has led to varied and complex models, with their own logic and different geographical limits, whose validity and underlying assumptions require testing in the light of current global geological and geophysical data. Our analysis of these models and their consequences on the continental passive margins brings to the fore critical scientific questions and the incoherencies that exist between them. This paper presents a compressive study of the structure of the Precambrian basement, Paleozoic marginal and rift basins of the plates constituting the Indian Ocean, examining the architecture and geochronological composition of their composing Cratons and crustal blocks, and delineating important structural markers to juxtapose them in full-fit reconstructions. We introduce a new holistic model from Gondwana's initial geometry to Chron 34, achieved through a combination of onshore and offshore geological and geophysical data. Our new model is coherent with current data interpretations of major structures across the Indian Ocean. Consistent with the interpretation of the Beira High as continental crust, and recent seismic refraction interpretation of the Pamela MOZ3-5 expedition in the Northern Mozambique Ridge and Northern Natal Valley. The model also permits full extent of major cratonic, volcanic and sedimentary structures within the supercontinent, and presents a new synthesis upon which further work may be projected.

Keywords : Gondwana, Plate tectonics, Indian Ocean, PanAfrican structures, Amalgamation, Kinematic evolution

1.1 Introduction

The formation of Gondwana during the PanAfrican Orogeny and its subsequent fragmentation in the Jurassic saw the largest unit of continental crust on Earth live for more than 200Ma, but the question of the initial geometry of this super landmass remains unanswered and a challenge to geologists. Any attempt to describe the plate tectonic history of Gondwana must first begin with a discussion of the initial fit. However, reconstruction models of the Indian Ocean are characterized by gaps and overlaps whose approaches and underlying reasons may have to be investigated to understand the differences.

The early breakup history between East and West Gondwana is preserved in the Indian Ocean along the East Africa, Madagascar, and Antarctica passive margins (Figure 1) (McKenzie & Sclater, 1971; Smith & Hallam, 1970; Tarling, 1972; De Wit *et al.*, 1988; Sahabi, 1993; Konig & Jokat, 2006; Eagles & Konig, 2008; Leinweber & Jokat, 2012; Seton *et al.*, 2012; Torsvik *et al.*, 2012; Gaina *et al.*, 2007, 2013, 2015; Reeves, 2014; Reeves *et al.*, 2016; Davis *et al.*, 2016). These margins recorded the oldest sediments and magnetic anomalies of the Indian Ocean, and are therefore crucial to our understanding of the initial configuration of Gondwana and its early breakup history at Jurassic time. Although the Cenozoic kinematic history of the ocean is well constrained between the plates (Bernard *et al.*, 2005), the question of the pre-breakup geometry and history of Gondwana is still debated, due to the lack of quality geological and geophysical data, and difficulties in interpreting magnetic anomalies along the margins, which could provide information on the age of the underlying crust, their spreading regimes and constraints on first horizontal movements (Leinweber & Jokat, 2012). This phenomenon has resulted in varied data interpretations and model predictions based on different data sets, leading to diverse initial fit positions (Figure 2). Researchers adopt different approaches to the reconstruction modeling: Konig & Jokat (2006), Eagles & Konig (2008), Torsvik *et al.* (2012), Gaina *et al.* (2013), Nguyen *et al.* (2016), Davis *et al.* (2016) adopt a model predominantly based on geophysical data (gravity and magnetic data); the modeling of Tarling (1972) and Powell *et al.* (1980) is based on onshore geological data, with less consideration of geophysical data; those of Torsvik *et al.* (2008, 2012), Muller *et al.* (1997) are based on hotspot tracks. Lastly, others consider only a part of the problem by focusing on a specific area without regard to the consequences on the distant boundaries of the plates (e.g. Klimke & Franke, 2016).

Within the framework of the PAMELA (Passive Margin Exploration Laboratories) project, which is an integrated research project co-funded by TOTAL and IFREMER, in collaboration with Université de Bretagne Occidentale, Université Rennes 1, Université Pierre and Marie Curie, CNRS and IFPEN, on passive margins across the globe, we attempt here to highlight the varied differences and incoherencies in current published models (McKenzie & Sclater, 1971; Smith & Hallam, 1970; Tarling, 1972; Sahabi, 1993; Konig & Jokat, 2006; Eagles & Konig, 2008; Leinweber and Jokat, 2012; Seton *et al.*, 2012; Torsvik *et al.*, 2008, 2012; Gaina *et al.*, 2013, 2015; Reeves, 2014; Reeves *et al.*, 2016; Davis *et al.*, 2016) by plotting such models on the same scale to compare them (Figures 2 and 3). The most recent models (Reeves & de Wit, 2000; Konig & Jokat, 2006; Eagles & Konig, 2008; Leinweber *et al.*, 2012; Seton *et al.*, 2012; Torsvik *et al.*, 2012; Gaina *et al.*, 2015; Reeves *et al.*, 2016; Davis *et al.*, 2016; Klimke & Franke, 2016) overlap some hundreds of kilometers across the African continent and the Mozambique ridge raising questions as to the nature of the crust underlying these areas and the implication on the Limpopo Margin and the connected Fracture zone (Figures 1 & 3). In addition, they pose questions about the latitudinal and angular position of Madagascar and India relative to Africa, as their positions vary widely in these models, which in turn may imply different pairs of conjugate passive margins (Figure 3). We then present a new model of

East-West Gondwana's initial fit based on analysis and combination of onshore and offshore geological and geophysical data. This model entails pronounced consequences for some specific features in this area: Beira High in coherence with new results of Mahanjane (2012) and Mueller *et al.* (2016), Mozambique Lowland also in agreement with new results of MOZ3/5 experiment (Lepretre *et al.*, 2017; Verrier *et al.*, 2017, Moulin et al., Submitted).

1.2 Previous reconstruction models

Notwithstanding the dedicated research efforts and scientific knowledge that confirms the continental drift processes and the Wilson cycle (e.g. Rodinia, Gondwana, Pangea, etc.), a crucial scientific question which still remains unanswered is: what was the initial geometry of Gondwana and how did its disintegration occur? This question is critical to deciphering how the plates were positioned relative to each other. Although there has been a number of attempts to find some answers over the decades, to date, the answers so far differ widely, and currently there is no consensus on the initial fit (See also http://www.reeves.nl/gondwana). Figure 3 is a zoom on selected kinematic reconstruction models (Sahabi, 1993; Leinweber & Jokat, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2016; Davis *et al.*, 2016; Klimke and Franke, 2016) of Figure 2.

Figure 3(a) shows the relative position of Madagascar in respect to Africa in the four models. Notice how Madagascar is differently placed in the models in terms of latitude and orientation.

In the models of (Sahabi, 1993; Leinweber & Jokat, 2012; Reeves *et al.*, 2016; Davis *et al.*, 2016), Madagascar fits more obliquely to Africa, as opposed to that of Gaina *et al.*, (2013) and Klimke and Franke (2016), who proposed a relatively N-S position. Besides the fact that this divergence implies different conjugate passive margins for the Majunga Basin and therefore has strong consequences on the understanding of the genesis of this margin, the angular and latitudinal position of Madagascar has strong implications on the position of the rest of Gondwana's plates relative to Africa assuming they were all connected (e.g. Mad/India/Ant). Reeves *et al.* (2016) implies overlap between the Africa plate and part of Madagascar, two thick continental crusts. If this is true, it must question the existence of a significant intraplate deformation in the Tanzania area, which may compensate this overlap by an internal movement inside the African plate.

Southwards with a focus on the Antarctica Plate (Figure 3b), Leinweber and Jokat (2012), Gaina *et al*. (2013), Reeves *et al*. (2016) and Davis *et al*., (2016) all overlap the Antarctic plate across the Mozambique Lowland, presuming oceanic origin for the basin, without considering the N-S continuity of the Limpopo Margin and the following fracture zone to the South. Sahabi (1993) avoids such an overlap, considering the basin to be continental in origin. Additionally, other critical questions that still remain unanswered include: the origin of Gondwana's breakup (whether the Karoo volcanic event provided the essential trigger for the breakup of Gondwana, or may have been controlled by the ultimate positioning of major fault systems within the supercontinent, which may have been subsequently exploited in a later event to disintegrate the supercontinent), the age range of the rifting, the position of the Continent-Ocean Transition Boundary (COB) across the Mozambique basin, the oldest oceanic crust in the Mozambique basin (whether magnetic anomaly M41 (166 Ma, Leinweber *et al*., 2012) represents the first ocean in the basin or may correspond to magmatic underplating (Mueller and Jokat, 2017)), and the crustal nature of the Mozambique and Madagascar aseismic ridges.

2. Methology

Producing as realistic as possible a holistic and coherent reconstruction of the Indian Ocean demands a multifaceted approach (Aslanian *et al*., 2009; Moulin *et al*., 2010; Aslanian & Moulin, 2012) through detailed analysis and interpretation of verified onshore and offshore geophysical (seismic, gravity, magnetic, and bathymetry) and geological (stratigraphic, structural and tectonic, geochemical and geochronogical data) data from the margins and adjoining plates, within a global view, and also to produce, with continuous feedback from both detailed and global studies, a model that is consistent and respectful of current data interpretations and field observations.

We first carried out a comprehensive examination of a number of large, but not exhaustive published kinematic reconstruction models of the Indian Ocean, (more than 30 since 1977) to compare them on the same scale and with the same geographical view using PLACA (Matias *et al.*, 2005) and PLACA4D (Pelleau *et al.*, 2015) softwares, looking at their consequences on the continental passive margins and predictions on the nature and origin of the Mozambique and Madagascar aseismic ridges.

We then undertook a compressive study of the basement of the plates: looking at the architecture and geochronological composition of their constituent Cratons and crustal blocks and delineating important structural markers to accurately juxtapose them to obtain a more coherent initial fit. Indeed, Gondwana formed during the PanAfrican Orogeny from ca. 720 to 550Ma (Hurley *et al.*, 1967; Trompette, 1994; Jacobs *et al.*, 2003; Guiraud *et al.*, 2005), consisting of Archean and Paleoproterozoic Cratonic cores, surrounding accreted progressively younger orogenic systems of Mesoproterozoic and Neoproterozoic age (Jacobs *et al.*, 2003; de Waele, 2003; Guiraud *et al.*, 2005; Jacobs *et al.*, 2008; Rekha *et al.*, 2014). The amalgamation of Gondwana initiated during this period, through the closure of a number of large ocean basins and the collision of several Cratonic blocks (e.g the closure of the Mozambique Ocean between the Dharwar Craton and Tanzania Craton) (Cox *et al.*, 2012, Tucker *et al.*, 2014) to form the largest unit of continental crust on Earth for more than 200Ma from the Late Neoproterozoic 550 Ma to the Carboniferous at about 320 Ma (Torsvik and Cock, 2013). Its progressive rifting from the Paleozoic was facilitated by the rejuvenation of late Proterozoic zones of lithospheric weakness, and major fault zones, which were paleo-orogenic-rift zones, leading to the formation of rift basins (Karoo Basins) and volcanic intrusions. Consequently, in-depth knowledge and understanding of the structure of the Archean-Proterozoic basement geology of Gondwana, its conjugate plate structural markers, Paleozoic margins and rifts basins are very critical to unraveling the initial geometry of Gondwana and its disintegration.

A compilation of accessible onshore and offshore geological and geophysical data in the Indian Ocean was therefore carried out, to apprehend the work already achieved, and to identify the main challenges and scientific questions that exist in the ocean. A compilation of the lithotectonic sequence and magmatic events of the Karoo basins and Karoo event along the East African margin, and within the African plate was compared to Karoo events in Madagascar, Antarctica, and Australia to examine the different lithological sequences that were deposited from the Late Carboniferous to Recent, and also to understand the evolution of these basins.

A reconstruction needs to take into account the geometry and the nature of the passive margins as well as the main structural oceanic features produced by the breakup and dispersion of Gondwana (Aslanian & Moulin, 2012). Published reflection and wide-angle seismic data (Leinweber *et al.*, 2011; Mueller and Jokat, 2017; Fischer *et al.*, 2017) as well as industrial seismic profiles (in Tanzania, Morondava, Majunga, Zambezi and Natal Basins) were used to delineate oceanic, continental and transitional domains and to identify some major fault structures and directions of fault propagation.

Current geochemical and geochronological data on the basement geology and structural markers of all the adjoining plates of the Indian Ocean were examined and compiled to help constrain the initial fit. Plotting of the maps presented here was achieved using Arcgis 10.2, PLACA software (Matias *et al.*, 2005) and Generic Mapping Tool (GMT) (Wessel and Smith 1998).

In our reconstructions and figures, we use the actual shape of the coastlines, where we assumed an unthinned substratum. Gaps and overlaps, which may appear, must be explained by intraplate deformation that may have occurred after the breakup and deformed the shape of the coastlines since the breakup, and/or the presence of continental material offshore the coasts. If no evidence of such material or deformation is observed, the reconstruction must be modified (Moulin *et al.*, 2010; Aslanian & Moulin, 2012). Therefore, in a given reconstruction, an overlap is explained by the existence of a basin younger than the age of the fit: if it exists, the palinspastic reconstruction of this basin (completely or partially produced by horizontal movements – Aslanian *et al.*, 2009) may reconstruct the shape of the coastline before the formation of the basin and reduce or erase the overlap. In the same way, a gap is explained either by the existence of continental block offshore and/or by the existence of a range on the rear side of the coastline, younger than the age of the fit: the deployment of this range may fill the gap (and change the shape of the coastline).

Reeves *et al.*, (2016) assume, by analogy with current passive margins, that the pieces of Precambrian crust that still exist in their full thickness, are separated by belts of about 250 km of extended crust; assuming a thinning factor ß between 2 and 4, they proposed an assemblage of these Precambrian blocks at 182.7 Ma with a separation of about twice the typical crustal thickness (i.e. about 80 km, but +/- 20 km). Whilst this attempt is a good first approximation it needs, as these authors wrote: « More works […] to be done to quantify [their] assumption »: indeed, current knowledge on the morphology of present margins around the world presents a very different view of passive margins, with very different morphologies. It seems to us more sensible to separate the pre-breakup evolution into two steps, as we obtain ever more geophysical data and evidence on margins and offshore. Having a well-constrained reconstruction at the breakup time will give us a good base to test Reeves *et al.* hypothesis.

Finally, all our findings and interpretations from the different data sources were combined to propose a new pre-breakup fit of Gondwana. In May 2016, new wide-angle data were acquired in the Limpopo Margin and the Natal valley (Moulin & Aslanian, 2016; Moulin & Evain, 2016; Lepretre *et al.*, 2017; Moulin *et al.*, suubmitted) to determine the nature of the crust in these two basins. Their discovery of more than 30 km thick continental crust, underlying the two basins is fully consistent with our model.

3. Geological Constraints

Due to its central position in Gondwana, the Antarctica plate represents a crucial and pivotal plate in the paleogeographic history of the Indian Ocean; different parts of the plate share similar age and orogenic history with three neighboring plates: Africa, India and Australia (Boger, 2011).

Based on geochronological properties and similar orogenic history preserved in Antarctica compared to three of its neighboring plates; Zone 1 (blue rectangle in Figures 4 and 5) is related to the Kaapvaal Craton of Southern Africa, Zone 2 (red rectangle in Figures 4 and 6) is related to the Eastern Ghats rocks of Eastern India, and Zone 3 (yellow rectangle in Figures 4 and 7) is associated with the Australian plate, with a number of Cratons and continental blocks trending between the two plates (for e.g. the Gawler block of Australia forms an extension of the Mason block in Antarctica (Borg & DePaolo, 1991; Boger, 2011).

(a) Antarctica-Africa Structure of the Archean-Proterozoic basin (Zone 1 on Figure 4)

We have compiled from (Kelly *et al.*, 2002; Ghosh *et al.*, 2004; Boger, 2011; Riedel *et al.*, 2013) the geology of Antarctica (Figure 4) and from (Daly *et al.*, 1989: de Waele, 2003; Guiraud *et al.*, 2005; Jacobs *et al.*, 2008; Rekha *et al.*, 2014; Foster *et al.*, 2015) the geology of Africa (Figure 5) to delineate structural markers that trend between the two plates.

The Kaapvaal Craton (Figure 5) consists of Archean and Paleoproterozoic core surrounded by accreted younger terrains of Mesoproterozoic Namaqua-Natal and Neoproterozoic Pan-Africa orogenic belts (Jacobs *et al.*, 2003; de Waele, 2003; Guiraud *et al.*, 2005; Jacobs *et al.*, 2008; Rekha *et al.*, 2014; Riedel *et al.*, 2013). It bears geochemical signatures with the Grunneghona Craton, in Antarctica, most likely forming a single Craton at least during the latest Mesoproterozoic and Neoproterozoic times, and therefore provides evidence that the Droning Maud land (Figure 4) was situated south of the Mozambique belt in Gondwana (Thomas *et al.*, 1994; Jacobs *et al.*, 2008; Riedel *et al.*, 2013).

The Namaqua-Natal belt (Figure 5) was established during the Namaquan Orogeny in the Mesoproterozoic (1235±9 and 1025±8Ma) (Jacobs *et al.*, 2003). The eastern part of this belt, represented by the Natal belt consists of juvenile magmatic rocks formed between 1235±9 and 1025±8Ma (Jacobs *et al.*, 2003, 2008; Riedel *et al.*, 2013), with the main collisional event taking place at 1135Ma (Rekha *et al.*, 2014; Riedel *et al.*, 2013). It represents one of the very few areas of Mesoproterozoic crust in Gondwana that lacks significant overprint of the PanAfrican orogenic event (Jacobs *et al.*, 2003, 2008; Rediel *et al.*, 2013). In Antarctica, the contemporaneous Mesoproterozoic orogenic and magmatic activity that formed the Maud Belt (Figure 4) has been dated between 1171±25 to

1045±9Ma (Jacobs *et al.*, 1998, 2003). These two events may therefore be linked into one single Namaquan-Natal-Maud orogenic belt (Jacobs *et al.*, 2008). This provides important evidence in support of the Antarctic plate situated south of Mozambique at least during Mesoproterozoic times (Jacobs *et al.*, 2008; Riedel *et al.*, 2013).

Also, the Maud belt bears a number of similar characteristics with nappes of the Cabo Delgado Nappe Complex, north of the Lurio Belt (Figure 5; Bingen *et al.*, 2009), suggesting a common history between them.

The PanAfrican event is recognized in both Antarctica and Africa. Rocks of late Neoproterozoic-early Paleozoic age (580–550 Ma) are exposed between Western Dronning Maud Land and the Lutzow Holm Bay area in East Antarctica (Jacobs *et al.*, 2003; Riedel *et al.*, 2013). In Africa, the PanAfrican orogeny includes the Mozambique belt, southern Somalia and Ethiopia down to southern Africa.

Although large agreements exist on the similar geochemical signatures between the Grunneghona and Kaapvaal Cratons, and the extension of the Maud Belt to the Namaqua-Natal Belt, the question of the geometry of these structures and their extent still remains unanswered. In many reconstructions (e.g. Jacobs & Thomas, 2004; Konig & Jokat, 2006; Eagles and Konig, 2008; Leinweber & Jokat, 2012; Torsvik *et al.*, 2012; Seton *et al.*, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2016; Nguyen *et al.*, 2016), Antarctica (Grunneghona) overlaps directly the Mozambique Lowland some 300 km from the Mozambique shoreline. This assumption implies oceanic crust in the Mozambique Lowland, and has serious implications on the temporal and spatial evolution of the Mozambique margin. Duncan *et al.* (1997), Klausen (2009), Hastie *et al.* (2014) postulate the Mozambique Lowland to be floored by Karoo volcanics getting younger seaward (Watskey, 2002; Klausen, 2009) and aeromagnetic studies of dyke swarms of the Lebombo Mountains, which fringe the Mozambique Lowland, have been associated with rifting of Gondwana (Watkeys, 2002; Reeves 2000; Reeves & Mahanjane, 2013; Reeves *et al.*, 2016). The dykes are interpreted as products of successive stages in the interaction of the tectonic plates and intraplate fragments that underwent relative movement during the disruption of Gondwana (Reeves, 2000). Reeves (2000) postulates that the dyke swarms and the Lebombo-parallel dykes, are related to the initial east-west separation of Africa and Antarctica.

However, the geological analysis of the Karoo rocks (Melluso *et al.*, 2008) onshore in the Mozambique Lowland shows a composition, that is not of MORB composition, nor SDRs, as is inferred by all models, that overlap Africa and Antarctica. Moreover, Domingues *et al.* (2016), applying seismic ambient noise tomography in the Easern Rift system in Mozambique, addressed the question of the crustal nature of the Mozambique Coastal Plains (MCP). Their data show low crustal velocities that do not support the suggestion that the MCP is floored by oceanic crust. They suggested instead that the crystalline basement of the Zimbabwe craton may extend further east well into Mozambique underneath the sediment cover, with a thinning towards the eastern Limpopo margin, that they interpret as a possible transitional crust from continental to oceanic. This conclusion is coherent with Flores (1964, 1973) who observed that, instead of a continuous sheet of Karoo effusive underlying the basin, the basin may be characterized by series of parallel trending fractures issuing ever younger magma, which may have led to magnetic signatures.

Lastly, results from recent seismic refraction and reflection data acquisition in the basin (Lepretre *et al.*, 2017; Verrier *et al.*, 2017; Moulin *et al.*, submitted) show that the Natal Basin is not underlain by oceanic crust, but a 35k m thick crust of continental nature. This is in contrast to models that require overlap of Antarctica across the basin.

(b) Antarctica-India Structure of the Archean-Proterozoic basin (Zone 2 on Figure 4)

The geology of the India basement was compiled from (Ghosh *et al.*, 2004; Dasgupta *et al.*, 2013; Rajaprian *et al.*, 2014; Tucker *et al.*, 2014; www.portal.gsi.gov.in/portal 11/07/2016) (Figure 6).

Rocks of the Archean Napier complex of East Antarctica (Figure 4) link well into the Eastern Ghats Shield during Mesoproterozoic times (Kelly *et al.*, 2002: Ghosh *et al.*, 2004) together forming the "Indo-Napier segment'' described by (Ghosh *et al.*, 2004). The segment collided with the East Antarctic basement in

Mesoproterozoic during the amalgamation of Rodinia Supercontinent (Fitzsimons, 2000) producing the crustal fragments constituting the Rayner Complex. The Rayner Complex connects the Enderby Land with the Eastern Ghats Granulite Belt in India.

The geochronological data from the basement of Eastern Ghats and the Rayner - Napier complexes of Enderby Land East Antarctica, and a geometrical fit between the coastlines of the two plates (Biswal and Sinha, 2004, and Ghosh *et al.*, 2004) primarily permit a good juxtaposition of India to Antarctica in Gondwana. The juxtaposition is further enhanced by the conjugate Carboniferous-Permo-Cretaceous rift basins of Godavari and Mahanadi in Eastern India, and the Lambert and Robert rift valleys of Eastern Antarctica that bind the two plates (Kelly *et al.*, 2002; Ghosh *et al.*, 2004; Biswal & Sinha, 2004).

(c) Antarctica-Australia Structure of the Archean-Proterozoic basin (Zone 3)

The compilation of the Australian plate basement geology was based on the studies of Borg and DePaolo (1991) and Boger (2011) (Figure 7).

The Mawson block continues from Antarctica into the Gawler block in Australia (Borg and DePaolo, 1991; Boger, 2011). The Gawler block is a geochronological correlation with the rocks exposed in the Miller and Shackleton Ranges of the Mawson block (Boger, 2011).

The Beardmore block of Antarctica also bears similar geochronogical properties with the Curnamona block in Australia. According to Boger (2011), the Curnamona-Beadmore blocks collided with the Mawson block during the Paleoproterozoic Nimrod–Kimban orogeny (Boger, 2011).

Furthermore, a number of Mesoproterozoic blocks named Mesoproterozoic A (1.65-1.55Ga), Mesoproterozoic D (1.35-1.15Ga), Mesoproterozoic E (1.1-1.05Ga) by Boger (2011), can be traced to their conjugates in Antarctica bearing similar geochemical and age characteristics. The above geological data combined with the recorded geophysical data (magnetic anomalies from C34 to C0 - Cande and Mutter, 1982) and the gravity and bathymetry data between the plates, make their reconstruction the least complicated among all Gondwanan plates.

(d) India-Madagascar Structure of the Archean-Proterozoic basin

The geology map of Madagascar was compiled from the studies of (Besairie & Collignon, 1972; Courrier and Lafont, 1987; Nessen *et al.*, 1988: de Wit *et al.*, 2001; Rasoamalala *et al.*, 2014; Tucker *et al.*, 2014: Rekha *et al.*, 2014) (Figure 8).

The Archean sequence in Madagascar is represented by Archean rocks outcropping in Antongil and Masora, flanked by mostly juvenile granite–greenstone belts of Neoarchean and Paleoproterozoic rocks of Antananarivo (2.5–2.45 Ga; Tucker *et al.*, 2014). The Archean rocks in Madagascar share similar geochemical properties with the Western Dharwar Craton in India, permitting traces of significant geological structures into the two plates and their juxtaposition.

In addition, the Karrur Kambam, Palghat and Moyar shear zones are major structural markers in India (de Wit *et al.*, 2001: Ghosh *et al.*, 2004; Rekha *et al.*, 2014; Tucker *et al.*, 2014; Reeves *et al.*, 2014) whose conjugate structures (Ranostara, Angavo-Ifanadiana and Betsimisaraka Shear Zones) can be traced from Madagascar into India on the basis of similar geochronological history.

(e) Madagascar-Africa Structure of the Archean-Proterozoic basin

The Dharwar Craton (Figure 6) collided with the Tanzania Craton (Figure 5a) during the East African orogeny, leading to the closure of an ocean that previously separated them (Collins & Pisarevsky, 2005; Cox *et al.*, 2012; Tucker *et al.*, 2014). The protolith of the Bur Acaba (Africa) continental block share similar geochemical and geochronological properties with the Late Archean rocks of the Antananarivo Domain (2.75-2.50 Ga) (Kuster *et al.*, 1990; Lenoir *et al.*, 1994; Tucker *et al.*, 2014) and suggest that the Craton may have extended into Bur Acaba and beyond. According to de Wit (2003) and Ghosh *et al.*, (2004), Madagascar's east coast originated together with rocks of the Indian Dharwar Craton and was united for more than 3000 Ma. Other parts of Madagascar have African roots that go back 2500 Ma (de Wit, 2003; Ghosh *et al.*, 2004). The Neoproterozoic granulites of Madagascar (Vohibory domain) and Africa (The

Cabo DelGado nappes of the Mozambique belt) share similar geochemical properties (Bingen *et al.*, 2009; Tucker *et al.*, 2014). According to Tucker *et al.* (2014), the Vohibory represents a fragment of an exotic terrane, created when the paleo-Mozambique Ocean was sutured to the Androyan domain in the early Ediacaran time (0.65– 0.63 Ga).

(f) Falkland-Africa Structure of the Archean-Proterozoic basin

The Falkland Islands is currently agreed by a number of authors (Greenway, 1972; Martin *et al.*, 1982: Martin & Hartnady, 1986; Thomas *et al.*, 1997; Curtis & Hyam, 1998; Jacobs *et al.*, 1998) to form the missing southeastern extension of the Cape Fold Belt in Southern Africa, providing constrain on the original lateral extent of this orogenic belt in Gondwana. The Falkland island fit reconstruction to Southern Africa shows good correlation in both structural style and timing of deformation with the Cape Fold Belt (Lock, 1978; Martin *et al.*, 1982; Marshall, 1994; Ben-Avraham *et al.*, 1997; Curtis & Hyam, 1998), providing some support for the 90° counterclockwise rotation and emplacement of the Falkland Islands to its original position adjacent to southeastern Africa (Martin *et al.*, 1982 and Marshall, 1994). The oldest rocks making up the Falkland plateau are Mesoproterozoic basement (980-1100 Ma, Jacobs *et al.*, 1998) (Figure 9) exposed at Cape Meredith on the southern side of West Falkland, comparable to the Pre-Cambrian basement of Natal and East Antarctica.

The striking similarities between the geology of the Natal Belt, Cape Meredith, and the Heimefrontjella was summarized by (Marshall, 1994; Thomas *et al.*, 1997; Jacobs *et al.*, 1998) in favor of the three areas forming part of 1.1Ga Mesoprotorozoic terrain that was accreted to the Kaapval-Grunehogna Craton during Mesoproterozoic times. The terrain was partially rejuvenated during the PanAfrican orogeny (Thomas *et al.*, 1997; Jacobs *et al.*, 1998). Marshall (1994) presented Karoo stratigraphic correlation in support of a northern extension of the Falkland basin to the Outeniqua Basin (Southern Africa) at least during the Early Cretaceous.

(g) Sri Lanka Proterozoic basement geology

The geology of Sri Lanka was described according to Kelley *et al.* (2002), and Tucker *et al.* (2014) (Figure 10). The basement consists of the Paleoproterozoic Wanni, Highland and Vijayan complexes, which were overprinted by the Pan-African orogenic event. The Vijayan complex shares similar geochronological properties with Lutzow Hölm Complex of Antarctica (Kelley *et al.*, 2002; Bingen *et al.*, 2009; Tucker *et al.*, 2014; Rekha *et al.*, 2014) and therefore allows for reconstruction of Sri Lanka to the Lutzow Hölm area.

3.2 Paleozoic margins and basins, and mountain belts and rifts

The Paleozoic marginal and rift basins of Gondwana preserve the litho-stratigraphy history of the supercontinent from the Late Carboniferous to the Middle Jurassic. From the Late Carboniferous, Gondwana experienced varying magnitudes of intraplate deformation and volcanism most often centered along pre-existing fractures and fault zones within orogenic mobile belts and Cratonic boundaries (Watkeys & Sokoutis, 1998). The beginning of the fragmentation of Gondwana was accompanied by the formation of a series of interior fracture basins (Salman & Abdula, 1995), which were filled by sediments represented by the Late Carboniferous–Early Jurassic sedimentary Karoo Supergroup in Africa, Madagascar, Antarctica, Australia and India.

The formation of these basins and their sediment deposition was mainly controlled by the interaction of tectonics (compressional and extensional deformation) and climate, providing similarities in their development (Catuneanu, 2004; Guillocheau & Liget, 2009). The tectonic deformation varied from predominantly flexural in the south, in relation to processes of subduction, accretion and mountain building along the Panthalassan margin which led to the establishment of the remnant Cape Fold belt, and the retroarc foreland Main Karoo Basin in Southern Africa (Bordy & Catuneanu, 2001; Catuneanu, 2004; Guillocheau & Liget, 2009) andto extensional deformation along Eastern Africa and Madagascar margins linking the Tethyan rifts (Kazmin, 1991; Gnos *et al.*, 1997) to establish the Karoo rift basins along these margins.

In Madagascar, the Karoo rifting event is represented by Sakoa, Sakemena and Isalo formations in the Morondava and Majunga basins from Upper Carboniferous to Mid-Bathonian mainly composed of continental red-bed sedimentation (Geiger *et al.,* 2004). The deposition of these sediments was largely controlled by faults as a response to crustal stretching and thinning.

In Africa, the Karoo sequence is identified in the Karoo Basins of Eastern and Southern Africa. It is a thick sequence in the Middle Zambezi Valley, a thin sequence west of Beira and a thin sequence above the basement in southernmost Mozambique (Salman & Abdula, 1995, Mahanjane, 2012). In Southern Africa, the Late Carboniferous–Early Jurassic sedimentary Karoo Supergroup is composed by the Late Carboniferous Early Permian Dwyka Formation, the Permian Ecca Formation, the Late Permian to Early Triassic Beaufort Formation, and the Late Triassic to Lower Jurrassic Stormberg Formations. The Karoo sequence is capped by the Lower-Middle Jurassic Karoo volcanics.

In Antarctica, it is represented by the Permian to Jurassic sediments of the Transantarctic Mountain (Elliot & Fleming 2004) and the volcanic intrusions of the Dronning Maud Land (Duncan *et al.*, 1997). In Australia, it is represented by the Paleozoic sediments and intrusives of Queensland and Tasman (Wellman & McDougall, 1974). For description of the evolution of the Karoo basins, the reader is referred to (Bordy and Catuneanu, 2001; Catuneanu, 2004; Salman & Abdula, 1995; Guillocheau & Liget, 2009).

The rifting was followed by vast intrusion of volcanism in Southern Africa (Lebombo Monocline and Karoo volcanics) and Antarctica (Volcanics of the Dronning Maud Land and the Ferrar Province) characterized by a vast network of sills and dykes (Karoo volcanism: Elliot & Fleming 2000; Hastie *et al.*, 2014). The Karoo volcanic event is contemporaneous with the intrusive components of Tasman dolerites in Australia (Wellman & McDougall, 1974; Wellman, 1983). Studies of the dykes in the Lebombo range (Africa), Dronning Maud Land, and Kirkpatrick basalts (Antarctica) and the Tasman dolerites (Australia) (Duncan *et al.*, 1997; Elliot & Fleming, 2000; Klausen, 2009; Hatsie *et al.*, 2014) have shown them to have compositional and age overlaps, granting some common history of their emplacement. Authors are currently divided on the interpretations and importance of the Karoo volcanic events in the evolution of the Indian Ocean. Debates are still ongoing as to whether the event caused Gondwana's breakup or not. However, the Karoo magma lacks comparable compositions of primitive plume magma (Riley *et al.,* 2005), and the long duration of the event, (lasting about 10Ma, Klausen 2009), compared to mostly short-lived 3-5Ma for plumes (Svensen *et al.*, 2012), argue against the association of volcanics with the plume. Moreover, the rhyolites show abnormally high K, Na, Sr and Ba compositions, which according to Bristow (1980), may have been sourced from the partial melting of previously underplated basaltic magma.

The Mbuluzi rhyolites and Rooi Rand Dykes (174Ma Ar/Ar; Klausen, 2009) of the Lebombo monocline was described as having Mid Ocean Ridge Basalt (MORB) like characteristics (Jourdan *et al.*, 2007; Klausen, 2009; Hastie *et al.*, 2014), and its emplacement coincident with the formation of first oceanic crust in the Mozambique Basin, about 20Ma older than the confidently dated oldest true magnetic anomaly in the basin (Jokat *et al.*, 2003). Theoretically, this assumption results in a sharp narrowing of the continent–ocean transition in the Mozambique basin, which has serious implications on the temporal and spatial evolution of the margin supposing oceanic crust east of the Lebombo monocline in the Mozambique Lowland. However, the analysis of the rocks (Melluso *et al.*, 2008) onshore in the Mozambique Lowland shows a geochemical composition, which fits neither a MORB composition nor SDR's.

3. 3 Offshore geological constraints

The determination of the true nature and origin of oceanic geological structures is not a straightforward task. Although there have been several attempts to describe the nature of offshore aseismic structures and basins in the Indian Ocean (e.g. Beira High, Maurice Ewing Bank, Mozambique and Madagascar ridges, the Mozambique Lowland and Northern Natal Valley), debates still exist on their crustal origins and whether they existed during the amalgamation of Gondwana or were formed sometime after its fragmentation. Fortunately, there have been recent efforts to acquire new geological and geophysical data to try to find some answers. We examine current published data on some of these key structures, as they have strong implications on the reconstruction of the Gondwana's initial geometry.

Aseismic Madagascar Ridge

The Madagascar Ridge is 400 km across, extending southwards from the Madagascar continent over 1300 km, with a water depth between 2 to 3km over most of the plateau (Figure 1).

The Madagascar ridge was first considered a continental extension of south of Madagascar by Heezen and Tharp (1965). DSDP 246 and 247 attempt to determine that the nature of the ridge could not reach basement due to hole instability (Schlich *et al.*, 1974). Whilst the data wide-angle seismic did not extend north of 30°S, and therefore, the Moho in this area is unknown, Goslin (1981) proposed a subdivision of the ridge into two distinct domains South of 32°S, the ridge presented wide-angle seismic evidence in support of oceanic origin, with a Moho located at 14 km, and represents the companion structure of the Del Cano Rise. Northwards, between 30°S and 32°S, the ridge is underlain by a strongly anomalous crust with a Moho located at a depth of 22 to 26 km (Recq *et al.*, 1979; Goslin, 1981) and is in local isostatic equilibrium with respect to the adjoining basins (Recq and Goslin, 1981).

Currently, the nature of the ridge is left to the determination of reconstruction models. Martin and Hartnady (1986) suggest that the alignment of the Madagascar plateau with the Del-Cano and Conrad plateaus suggests that their formation is related to activity of hot spots. Schlich *et al.* (1974) Goslin (1981) and Goslin and Patriat (1984) consider the south Madagascar ridge as conjugate to the Crozet plateau formed along the South West Indian Ridge (SWIR) between 90Ma-70 Ma. The reconstruction models of Smith and Hallam (1970), Norton and Sclater (l979) and Sahabi (1993) leave large gaps in southern Madagascar, which is filled by the northern part of the Madagascar ridge, presupposing continental origin.

Mozambique Ridge

The Mozambique ridge is formed of several bathymetric plateaus rising up to 3500 m from the seafloor, at the boundary between two Mesozoic oceanic basins that formed at different spreading regimes: the Early Cretaceous South Natal Basin connected with the movement of the Patagonia-Falkland sub-plate and the opening of the Southern part of the South Atlantic Ocean (Segment 3 in Figure 1) and the Upper Jurassic Mozambique segment (Segment 2 in Figure 1), connected with the southward mouvement of the Madagascar / Antarctica / India / Australia blocks. It has broad elevated topography on its southern half, and falls steeply into the Mozambique basin on its eastern side.

The nature of the Mozambique ridge and the North Natal Valley has been under debate for a long time (Tucholke *et al.*, 1981; Raillard, 1990; Mougenot *et al.*, 1991; Hartnady *et al.* 1992; Ben-Avraham *et al.*, 1995; Leinweber and Jokat, 2011; Gohl *et al.*, 2011; Fischer *et al.*, 2017). Its origin (whether continental or oceanic) has a large impact on the reconstruction of the Indian Ocean. An Oceanic origin implies it was formed sometime after the breakup of Gondwana and allows an overlap by other continental fragments; a continental origin means its existence precedes the breakup and cannot simply be overlapped by other continent plates, without any explanation as rift in the inner land, which may imply further horizontal movement (see example on South Atlantic Ocean: Moulin *et al.*, 2010 and Aslanian and Moulin, 2012).

A continental origin was favored by Tucholke *et al.* (1981) followed by Raillard (1990), Mougenot *et al.* (1991), when dredged samples of Archean fragments were retrieved along the eastern and southern Mozambique Ridge composed of anorthosites, gneiss and metagabbros (Martin *et al.* 1982). However, indications of a possible oceanic origin for the ridge came from first direct samples during DSDP leg 25 hole 249 (see location in Figure 1), where MORB-like rocks were retrieved (Thompson *et al.*, 1982). Mougenot *et al.*, (1990) and Ben Avraham *et al.*, (1995) proposed then, at least for the southern part of the ridge, the presence of a micro-continental fragment, with Moho depth of about 20-25km, embedded by oceanic crust.

Recently, Gohl *et al.* (2011) provided seismic refraction evidence in support of the Southern Mozambique ridge having oceanic origins, possibly formed due to excessive volcanism at a triple junction. Fischer *et al.* (2017), analyzing seismic reflection data, observe the ridge to be composed of a large number of extrusion centers, and estimate the southern Mozambique Ridge to be emplaced between ∼131 and ∼125 Ma.

Within the framework of the PAMELA Project, several wide-angle and reflexion seismic profiles were shot during MOZ3-5 cruise. The results shows that the north-eastern part of the positive gravity anomaly, eastwards of the NNV, consists mainly of an alignment of sedimentary, probably contouritic, features covering a thinned continental crust (Leprêtre *et al.*, 2017; Moulin *et al.*, submitted).

Consequently, on the basis of the wide-angle seismic evidence by Gohl *et al.* (2011) Fischer *et al.*, (2017), Leprêtre *et al.* (2017) and Moulin *et al.* (submitted), we separate the positive gravity anomaly which seems to mark the Mozambique Ridge in two parts, with an oceanic crustal nature for the South Mozambique ridge, and a continental crustal nature eastwards of the NNV (figure 1).

Beira High and Zambezi Depression

The Beira High is approximately 280 km long and 100 km wide (Mahanjane, 2012), elongated in northeast-southwest direction, and subparallel to the Zambezi coastline. It is located in water depth between 1000 to 2500 m and buried by Mesozoic and Cenozoic sedimentary sequences (Mahanjane, 2012: Mueller *et al.*, 2016). The question of the origin of the Beira High has been controversial for a long time. Leinweber *et al.*, 2013 interpreted Mesozoic magnetic series from M28 to M41. According to these authors, recent kinematic models (Leinweber and Jokat, 2012; Gaina *et al.*, 2013 2015; Davies *et al.*, 2016) have regarded its nature to be oceanic. However, Mueller *et al.* (2016) presented new wide-angle seismic and gravity data and their study concluded on a continental nature for the Beira High, and a possible thinned/stretched intruded continental crust for the Zambezi depression, north of Beira High (Figure 11). This result confirms the interpretation of Mahanjane (2012) showing extensional deformation and breakup unconformity reflectors downlapping against the acoustic basement along the eastern flank of the Beira High. These new data and results refute an overlap of the Antarctic plate on the Beira High.

Natal Valley

The North Natal Valley (NNV) stretches between longitude 33-36°E and latitude 25-28°S (Figure 1) and has a key position in the Gondwana breakup. While the recognition of Mesozoic magnetic anomalies from M12 to M0 clearly shows the presence of an oceanic crust in the South Natal Valley (Goodlad *et al.*, 1982; Martin *et al.*,1982), the NNV is subject to controversies as its magnetic signature is hardly lisible. Marks and Tikku (2001) and Tikku *et al.* (2002) identified anomaly M10 and M4 in the valley and Leinweber and Jokat (2011) identified SW-NE trending magnetic anomalies within the NNV, suggesting it to be floored by thickened oceanic crust with the Continent Ocean Transitional (COT) lying close to the Lebombo range. This hypothesis allows Antarctica to overlap NNV and is followed by the most recent kinematic models (see Figures 2 and 3).

The wide-angle and reflexion seismic results of the MOZ3-5 experiment show evidence in favor of the North Natal Valley underlain by a 30-35 km thick continental crust (Lepretre *et al.*, 2017; Verrier *et al.*, 2017; Moulin *et al.*, submitted), which precludes an overlap of the Antarctic plate and the NNV.

Maurice Ewing Bank

The Maurice Ewing Bank (MEB) represents the easternmost portion of the Falkland plateau (Figure 9). DSDP Hole 330 shows Precambrian granitic and metasedimentary gneissic rocks only a few meters below fossiliferous Jurassic sediments (Ben-Avraham *et al.*, 1995) to confirm continental origin for the MEB. The Precambrian rocks recorded Rb/Sr isochron age of 554± 66 Ma (Lorenzo and Mutter, 1988) correlative with the similar age granite of the Cape sequence of Southern Africa (Thomas *et al.*, 1997; Jacobs & Thomas, 2004; Riedel *et al.*, 2013).

The Tugela ridge, an E-W elongated structure offshore South Africa at 30°south, is presumed to be the effective northern limit of the Natal Valley beyond which the MEB cannot be accommodated (Martin *et al.*, 1982; Goodlad *et al.*, 1982; Curtis and Hyam, 1998). Goodlad *et al.*, (1982) and Martin *et al.*, (1982) suggest therefore that the Tugela ridge marks the COB in the Natal Valley. The newly acquired seismic data of the MOZ3-5 experiment tend to support their assertion (Leprêtre *et al.*, 2017; Moulin *et al.*, submitted). .

4. Initial fit reconstruction: previous models

We present here an analysis and comparison of eight (Sahabi, 1993; Leinweber and Jokat, 2012; Torsvik *et al.*, 2012; Seton *et al.*, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2016; Nguyen *et al.*, 2016; Davis *et al.*, 2016) recent palinspastic models of the Indian Ocean. These models vary widely in their initial fit positions mostly occasioned by the use of different data sources and varied data interpretations. They were selected for analysis and comparison, with the same scale and geographical limits, to highlight their differences and consequences on the evolution of the margins, on the basis of current geochemical and geochronological data from basement geology, and important structural markers that we have been able to delineate on the various plates.

(a) Antarctica-India

Figure 12 compares the reconstruction of India-Antarctica of several authors (Sahabi, 1993; Leinweber & Jokat, 2012; Seton *et al.*, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2016; Nguyen *et al.*, 2016).

Notice Seton *et al.* (2012), Gaina *et al.* (2013), Nguyen *et al.* (2016) misfit of Archean rocks of the Napier complex and the Eastern Ghat Shield, and the conjugate Gondwana rifts basins (red boxes in Figure 12): Gaina *et al.* (2013) and Nguyen *et al.* (2016) results in an overlap of ~250km and ~150km of the India plate over the Antarctic plate respectively. In contrast, Sahabi (1993), Leinweber and Jokat (2012) and Reeves *et al.* (2016) present a perfect alignment of Archean rocks of the Napier complex and the Ghat Shield, as demonstrated by fieldwork by Ghosh *et al.*, 2004. Good alignment of Gondwanan rifts basins and the Mesoproterozoic rocks is also achieved in these three models. Notice however, the ~450km overlap of the north-east of the India plate on the Antarctica plate in Leinweber and Jokat. (2012) and Reeves *et al.* (2016).

(b) India-Madagascar

Figure 13 compares the fit between Madagascar and India in the same models and the model of Ghosh *et al.* (2004).

The upper part of the figure shows that Seton *et al.* (2012), Gaina *et al.* (2013) and Nguyen *et al.* (2016) models result in about ~140km gap between India and Madagascar and inaccurately fits Mesoproterozoic rocks to Archean rocks between the two plates. The four other models do not present such a gap.

Sahabi (1993) fits the Moyar shear zone to the Betsimisaraka shear (red box in Figure 13), a structure argued by Tucker *et al.* (2014) to be non-evident.
According to the model of Ghosh *et al.* (2004) based on intensive fieldwork in these areas, Leinweber and Jokat (2012) and Reeves *et al.* (2016) propose tight models, which correctly align the Agavo Ifanadiana shear zone with the Moyar shear zone, resulting in Mesoproterozoic rocks of Ikalamavony in Madagascar fitted with Archean rocks Dharwar Craton in India.

(c) Falkland and Africa

Figure 14 presents a comparison in orange of the fit between Falkland and Africa in Konig and Jokat (2006) and Leinweber and Jokat (2012) and in green of the fit of Martin *et al.* (1982) and Martin and Hartnady (1986).

Notice that in Konig and Jokat (2006) and Leinweber and Jokat (2012) models, the Maurice Ewing Bank is beyond the limit of magnetic anomaly M12, which is supposed to be the oldest anomaly in this area (Martin *et al.*, 1982), and overlaps, far beyond the Tugela ridge (Martin *et al.*, 1982; Goodlad *et al.*, 1982; Curtis and Hyam, 1998), a significant part of the NNV, which is known to be of continental nature (Leprêtre *et al.*, 2017; Moulin *et al.*, submitted).

(d) Beira high, North Natal Valley and Mozambique Lowland

The area comprising **Beira high, North Natal Valley and** Mozambique Lowland has a central and key position in the Gondwana breakup.
In Figures 3c and 15, we examine the consequences of the most recent models on the Beira High continental block (in orange), the Mozambique Lowland and the North Natal Valley.
Based on interpretation of some presumed magnetic anomalies on the Beira High (Leinweber et al., 2013) and the North Natal Valley (Marks and Tikku, 2001; Tikku et al., 2002; Leinweber & Jokat, 2011), all the recent models since at least 2012 (Leinweber and Jokat, 2012; Torsvik *et al.*, 2012; Seton *et al.*, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2016; Nguyen *et al.*, 2016; Davis *et al.*, 2016) overlap the continental Beira high (Mahanjane 2012; Mueller *et al.*, 2016), the

Mozambique Lowland and the North Natal Valley. Konig & Jokat (2006), Leinweber & Jokat (2012) Gaina *et al.* (2013) argue that Karoo volcanism resulted in the final breakup of Gondwana and ended with a tight fit between East and West Gondwana, with the Antarctic plate overlap across the Beira high, the Mozambique Lowland and NNV.

However, according to Riley *et al.*, (2005), the Karoo lavas do not have comparable compositions to oceanic lavas or primitive plume sources: the magma also shows low 4He/4He ratios, contrary to high value for plume sources and may argue against the magma coming from a deeper source. Moreover, there is no evidence of oceanic affinity for the NMR and NNV (Melluso *et al.*, 2008; Hanyu et al., 2017) and the presumed magnetic anomalies on the Beira High and the North Natal Valley are infirmed by the recent wide-angle seismic results (Mueller *et al.*, 2016; Lepretre *et al.*, 2017; Hanyu *et al.*, 2017). On the contrary, these new results show the presence of thick continental crust in the Beira High and in the NNV (Lepretre *et al.*, 2017; Verrier *et al.*, 2017; Moulin *et al.*, submitted).

The model of Sahabi (1993) avoids Antarctica overlap of the North Mozambique ridge, NNV and Mozambique Lowland, which satisfies the new wide-angle result, but not the Beira high.

(a) Local and partial models

There is however another category of models focusing on two or three plates. The major problem with many such models is the lesser regard given to the impact of the models on surrounding plates and data constrain from other sources (Aslanian & Moulin, 2012).

Based on analysis of seismic profiles, Klimbe and Franke (2016) prefer and propose a more southward position of Madagascar, linking the Lurio belt to the Ranotsara shear zone. However, whatever the chosen connexion between the pairs of plates, the model leads to a gap of about 1000 km between Antarctica and the Zambezi coastal plain. Moreover, the Panafrican Shear zones are more in accordance with a position not too different from (Sahabi, 1993; Leinweber and Jokat, 2012; Reeves *et al.*, 2016: Davis *et al.*, 2016), which seem to correlate

Majunga and Lamu Basins (Leinweber and Jokat, 2012; Reeves *et al.*, 2016; Davis *et al.*, 2016), and the Morondava and Tanga-Mombasa basins (Sahabi, 1993). However, the position seems too tight, without any room for the passive margins, which are offshore, resulting in overlap of the continental crusts.

Recently, based on the discovery of Archaean zircons in Mauritius, rocks establish ancient continental crust beneath Mauritius. Aswhal *et al.* (2017) propose the existence of a Mauritius continental plate between the Mosara Craton in Madagascar and the Western Dharwar in India. This position is hardly acceptable as the corridor including La Réunion and Mauritius and Mascarene plateau is fringed to the north by a fracture zone, which ends at southern Madagascar.

5. Proposed model of Gondwana's initial fit

Our proposed initial fit of Gondwana (Figure 16) presents good alignment of delineated conjugate structural markers across the plates, and also takes into account current published geochronogical data from the basement of the plates and new results of wide-angle seismic data. We detail this model step by step in the following sections, for each connected pair of plates.

(a) Africa-Madagascar fit

For Madagascar and Africa (Figure 17) and according to age similarities, our model aligns the PanAfrican shear zone separating the Vohibory complex (Tucker *et al.*, 2014) of Madagascar to the PanAfrican shear zone in Tanzania (Collins and Pisarevsky, 2005; Reeves, 2014), and continues the Brava fault in Kenya with the Andreaparaty shear zone in Madagascar. This allows the Belet Uen fault to match the northern fringe of Madagascar. The Ranotsara shear zone in linked to the Tombo faults, which we propose may continue into the Aswa shear zone in Uganda (Collins & Windley, 2002; Reeves, 2014).

Reconstruction along this line permits perfect alignment of the Karoo basins in both Africa and Madagascar, allowing the Karoo age sediments mapped in southwestern and northwestern Madagascar to be aligned parallel to the Karoo sediments in the Selous and Lamu basins in Tanzania and Kenya respectively (light grey areas on Figure 17). The initial rifting between the two plates was accommodated within these basins in the Permo-Trassic (Catuneanu, 2004; Guillocheau & Liget, 2009) linking the Tethyan rift system and creating interior fracture basins along the margins to allow the deposition of the early Karoo sediments (Flores, 1964, 1970, 1973; Salman and Abdula, 1995).

The fit also allows a good view of the extent of the Neoproterozoic granulites of the Vohibory domain in Madagascar and the Cabo Delgado nappes of the Mozambique belt (Bingen *et al.*, 2009; Fritz et al., 2013; Tucker *et al.*, 2014), which share similar geochemical properties. We recall that the protolith of the Bur Acaba shares similar geochemical and geochronological properties with the Late Archean rocks of the Antananarivo Domain (2.75-2.50 Ga) (Tucker *et al.*, 2014).

(b) Madagascar-India fit

Our reconstruction between Madagascar and India (Figure 18a) is along the lines of Windley (1994), Rekha *et al.* (2014) and Tucker *et al.* (2014) who provide geological evidence for the continuation of the Dharwar Craton between India and Madagascar: the Western Dharwar Archean Craton and a number of Precambrian structures can be traced from India into Eastern Madagascar.

The Archean rocks of Antongil and Masora in Madagascar are surrounded by Neoarchean and Paleoproterozoic rocks from the eastern margin into Antananarivo (Figure 8) and can be juxtaposed to its conjugate Western Dharwar basement in India. We trace the Ranotsara shear to the Karrur Kambam shear zone in India (Rekha *et al.*, 2014), the Angavo-Ifanadiana high-strain zone (AIHSZ) in Madagascar to its conjugate marker the Palghat shear zone in India along the lines of Windley (1994) and the Betsimisaraka shear zone in Madagascar to its conjugate Moyar shear zone in India.

Such reconstruction grants a view of the full extent of the Dharwar Craton, and a good alignment of Late Archean and Mesoproterozoic rocks between the two plates in full-fit reconstruction. The reconstruction leads to a 100 km overlap between India and Africa (Figure 16). This is due to the poorly defined limits of the India plate in the Karachi area.

The Seychelles plateau, a relic of India composed of Precambrian crustal rocks (Jaeger *et al.*, 1989), fits between India and Madagascar.

(c) India- Antarctica fit

We reconstruct Antarctica and India fit (Figure 18b) on the basis of geochronological data (Fitzsimons, 2000; Kelly *et al.*, 2002: Ghosh *et al.*, 2004; Biswal & Sinha, 2004; Boger, 2011). We recall that rocks of the Eastern Ghats Shield and the Rayner - Napier complexes share similar geochronogical properties (Biswal & Sinha, 2004, Ghosh *et al.*, 2004; Boger, 2011): the Rayner Complex extends from Enderby Land into the Mesoproterozoic rocks of the Eastern Ghats Granulite in India. Their juxtaposition is further strengthened by the continuity of Gondwana Indian rift basins of Godavari and Mahanadi and Lambert and Robert rift valleys of Eastern Antarctica (Kelly *et al.*, 2002; Ghosh *et al.*, 2004, Biswal and Sinha, 2004). The ~120 km overlap between India and Antarctica within Southern Bangladesh is explained by a) the not clearly defined limits of the India plate within the region and b) characterization of the region by large compressional deformation.

(d) Antarctica-Australia fit

The reconstruction of Antarctica and Australia fit (Figure 19) is the least complicated of all the Gondwanan plates. This is due to several Cratons and continental blocks that are identified continuing between the two plates. Our reconstruction was achieved on the basis of the geochronological data of Borg and DePaolo (1991) and Boger (2011). The Mawson and Beardmore blocks can therefore be juxtaposed to their conjugate Mason and Curnamona blocks in Australia, and the Mesoproterozoic A (1.65-1.55Ga), Mesoproterozoic D (1.35-1.15Ga), Mesoproterozoic E (1.1-1.05Ga), can be traced to rocks of similar geochronological ages in Antarctica.

(e) Antarctica-Africa-Falkland fit

Our reconstruction for this pair of plates (Figure 20) was achieved on the basis of the geochronological and geochemical constraints (Daly *et al*., 1989; Kelly *et al*., 2002; de Waele, 2003; Ghosh *et al*., 2004; Guiraud *et al*., 2005; Jacobs *et al*., 2008; Boger, 2011; Riedel *et al*., 2013; Rekha *et al*., 2014) between the two plates. We recall that 1) Archean rocks of the Kaapval Craton bear strong geochemical signatures to the Grunneghona Craton and therefore suggest that these two Cratons were connected before Gondwana's breakup; 2) the Namaqua-Natal-Maud belt was established during the Namaquan Orogeny in the Mesoproterozoic (1235±9 and 1025±8Ma) (Jacobs *et al*., 2003) and 3) the Maud Belt is the extension of the Namaqua-Natal Belt in Antarctica, and provides evidence in support of the Antarctica plate situated south of Mozambique at least during Mesoproterozoic times (Jacobs *et al*., 2008 and Riedel *et al*., 2013). We therefore align the two boundary faults of Archean Kaapval and Grunneghona Cratons (Tankard *et al*., 2009) and their Mesoproterozoic orogenic zones. The position is further strengthened by the new information from seismic studies (Domingues *et al*., 2016; Mueller *et al*., 2016; Lepretre *et al*., 2017; Verrier *et al*., 2017, Moulin *et al*., submitted) on the continental nature of the basement in the Mozambique Lowland and the NNV, and on the Beira High (dotted blue line in Figure 20), which prohibits overlap of Antarctica on these structures.

The main problem regarding Patagonia-Falkland reconstruction with respect to Africa is related to the different interpretations ascribed to the Gastre Fault System (GFS). This fault system has been described as a transcontinental ~500 km dextral deformation during the fragmentation of Gondwana (Rapela *et al*., 1991). Franzese and Martino (1998) contradicted Rapela *et al*., (1991) suggesting mainly oblique reverse deformation. Recently, based on field observations, Gosena and Loske (2004) and Zaffarana *et al*. (2010) suggested that the rocks associated with the GFS do not show evidence supporting the existence of a major dextral fault system. Currently, the amount of displacement, and the timing of the deformation remains a subject of debate.

However, with the new wide-angle seismic results in the NNV (Leprêtre *et al*., 2017; Moulin et al., Submitted), reconstruction along the lines of Gosena and Loske (2004) and Zaffarana *et al*. (2010) without strike-slip deformation along the GFS, may result in a large gap between the Maurice Ewing Bank and their continental boundary in the North Natal Valley. We initiate ~250 km of strike-slip deformation along the GFS to firmly close the South Natal Valley.

(f) Africa-Sri Lanka-India fit

In our new model, the prominent 600 km long ENE-WSW trending Lurio belt (Viola *et al.*, 2008; Bingen *et al.*, 2009) continues eastward to follow the angle made between India and Sri Lanka, along the lines of Ghosh *et al.* (2004), and may account for the distinct differences between the Precambrian geology of the southern tip of India and Sri Lanka (Jamal *et al.*, 1999; 2001; Bingen *et al.*, 2009) (Figure 16).

6.1 Model consequence on offshore geological structures

The model is coherent with current geophysical and geological data interpretations of key offshore geological structures in the Indian Ocean; consistent with an oceanic origin of the South Mozambique and South Madagascar ridges evidenced by seismic and DSDP data on the ridges (Schlich *et al.*, 1974; Goslin, 1981; Thompson *et al.*, 1982; Ben- Avraham *et al.*, 1995; Gohl *et al.*, 2011; Fischer *et al.*, 2017), continental origin for the North Natal Valley (Martin *et al.*, 1982; Curtis & Hyam, 1998; Leprêtre *et al.*, 2017; Verrier *et al.*, 2017; Moulin *et al.*, submitted), the Maurice Ewing Bank (Martin *et al.*, 1982; Goodlad *et al.*, 1982; Lorenzo & Mutter, 1988; Curtis & Hyam, 1998; Ben-Avraham *et al.*, 1995, DSDP Hole 330), the North Madagascar ridge (Schlich *et al.*, 1974; Goslin, 1981) and seismic reflection results in support of a continental origin for the High the Beira High (Mahanjane, 2012; Mueller *et al.*, 2016).

6.2 Model Consequences on conjugate Paleozoic marginal basins in Africa, Madagascar and Antarctica

Apart from providing a better constraining of Gondwana's initial fit on the basis of published geochronological data and delineated structural markers, the new model also provides good fitting of conjugate basins of the various plates. Notice how perfectly the Karoo sediments of Madagascar and Africa align (Figure 17),

and the extent of Karoo and Ferrar volcanism in Africa and Antarctica (Duncan *et al.*, 1997: Reeves and de Wit, 2000; Jourdan *et al.*, 2005; Klausen, 2009).
Between Africa and Madagascar, we propose the conjugate basin of Morondava in Madagascar to be the Tanga-Mombasa basin, and that of Majunga basin to be conjugate to the Lamu basin in Kenya (Figure 17). This allows for the eastern margin of Karoo rocks mapped in SW Madagascar to be aligned with similar rocks in the Selous-Tanga Basins in Tanzania which is continues northeastward into the Lamu-Majunga conjugate Karoo basins to link the Tethyan rifts of peri Arabia-India (Reeves and de Wit, 2000).

A line of deep-seated intrusions across the NE terminus of the Selous and Tanga basins is effectively observed on satellite gravity data (Sandwell *et al.*, 2014) and was interpreted by (Reeves and de Wit, 2000; Reeves, 2014) to indicate the initial line of fracture of Madagascar away from the African continent. Reconstructions along this line allow for good accommodation of an initial East to Southeastward extension between Madagascar and Africa to allow the deposition of Karoo sediments before the final southward drift after breakup of the two plates.

Between Africa and Antarctica, our reconstruction fits the Riiser Larson Sea to its conjugate Zambezi basin on the basis of identified magnetic anomalies and fracture zones (Segoufin, 1978; Simpson *et al.*, 1979; Konig & Jokat, 2010; Leinweber & Jokat, 2012)

Between Antarctica and India, the Bengal basin of India fits its conjugate Enderby basin in East Antarctica with the alignment of the Gondwanan rift systems of Godavari and Mahanadi rift valleys of Eastern India and Lambert Rift and Robert rift valley of East Antarctica.

7. Evolution

The new fit changes significantly the position of the plates and their post-breakup evolution must be reviewed (Tables 1 to 7).

The magnetic anomaly identifications we used to constrain the Mesozoic evolution of the Mozambique and Somali Basins are from the compilation of Davis *et al.*, (2016) for the Somali Basin and Leinweber and Jokat (2012) for the Mozambique Basin and the conjugate Riiser Larsen Sea. The Cenozoic evolution history of the Mozambique/Antarctic corridor is according to Bernard *et al.*, (2005).

7.1 Pre-breakup history to formation of first oceanic crust (M25 ~154Ma, Kimmeridgian)

During the Late Jurassic, the East-West separation of Gondwana occurred contemporaneous with the closure of the Meso-Tethyan oceanic (Kazmin, 1991), when the Central Afghanistan block (Cimmeria plate) collided with Eurasia, and the oceanic space between them was finally obducted and subducted under Eurasia (Kazmin, 1991 and Gnos *et al.*, 1997).

In the Indian Ocean, the breakup of Gondwana was accompanied by active seafloor spreading in the Western Somalia and Mozambique Basins in the Oxfordian (161-155Ma), identifiable from Mesozoic series of magnetic anomalies with the confidently dated oldest magnetic anomaly M25 in the Mozambique, Somali (and Argo) basins.

In Western Somalia, our fit presents two pairs of conjugate margins between Africa and Madagascar, separated by the Aswa-Tombo faults system: Lamu-Majunga and Tanga-Mombasa-Morondava systems (Figures 16 & 17). The Majunga-Lamu system represents a pair of pure divergent conjugate margins. From the fit to Kimmeridgian, the movement of extension/exhumation follows the Tombo and the Beler Uen faults direction and is about 250km. To the west, Tanga-Mombasa-Morondava system presents a system of pull-apart margins, with a central divergent domain between two strike slip margins, along the Tombo fault and the African coast (Cabo Delgano Complex), which will be marked later by the Davie ridge.

Further south, our fit associates the Beira area to the Lazarev sea margin, and the Angoche Basin to the Riiser-Larsen sea margin (Figures 16 & 20). The boundary between these two systems is marked by the Southern Astrid Ridge, in Antarctica, and the presence of the microcontinental block of Beira High (Mueller *et al.*, 2016), in Africa. This complex area represents a buffer zone (Figure 1) at the corner of a pure divergent Mozambique margin and the strike-slip Limpopo margin. North to the Beira High, the Zambezi depression is supposed to be of thinned continental crust nature (Mueller *et al.*, 2016). In continuation of this depression, small but continuous SDRs are observed at the slopefoot (Anderson *et al.*, 2013). We proposed that these two structures imprint the first and failed attemp of breakup, which jumped, during the Kimmeridgian kinematic revolution, to the south, along the southern limit of the Beira High, as shown by the M25 magnetic anomalies on both plates.

In the Mozambique basin (Figure 21a), we suggest that the age of the first oceanic crust corresponds to the intrusion of the rhyolitic magma on top of the Belo Formation, and the deposition of the Kidulgallo shales and marls on top of the Amboni Formation in the South Tanzanian Basin. In the Morondava basin, the age corresponds to the deposition of Duvalia Marl (Mudstones) on top of the Sakanavaka Formation (sandstones).

In the North Natal Valley, according to our model, no horizontal movement is observed during this phase. Recent wide-angle seismic results suggested a 30-35km thick continental layer in the NNV, 1000m below the sealevel (Lepretre *et al.,* 2017). Following the proposition of Tozer *et al.* (2017) for the Parnaïba Basin in Brazil and the recent model of passive margins and continental basins genesis of Aslanian *et al.* (2019), this may by explained by an overloading of the continental crust due to mafic intrusions, which could have occurred during this phase.

Further South, at the boundary between the South Atlantic and the Indian Oceans, the austral African margin is composed of four hemi-grabben-style rifts (Algoa, Gamtoos, Plemtos et Bredasdorp) connected by the deeper Outeniqua Basin, fringed to the south by the Agulhas Fracture zone. This South Africa rift system (SARS) is part of Jurassic-Cretaceous Rift basins (Paton & Underhill, 2004), which presents a serie of structural faults, inherited from the East-West elongated Cape Fold Belt, and bended towards the South in their eastern extremities. In our model, the SARS is connected with the Kimmeridgian phase, which produced the first oceanic crust in the Indian Ocean with the southward movement of the East Gondwana blocks.

7.2 Kimmeridgian-Valanginian (M25– M15) (~154Ma-135Ma)

Davis *et al.*, (2016) note that the magnetic anomalies M24Bn through to M0r are interpreted in the Somali Basin as being similar in age, spreading rate, and spreading directions to the magnetic anomalies previously interpreted in the neighboring Mozambique Basin and Riiser Larsen Sea. The similarity between the two data sets allowed them to match the older magnetic anomaly picks by defining a pole of rotation for a single and cohesive East Gondwana plate. However, according to magnetic anomaly M15n (~135Ma), they found it is no longer possible to match magnetic picks from both basins maintaining plausible plate motions, a conclusion we also come to using the same magnetic data.

We were able to maintain a cohesive unit of East Gondwana (Antarctica, Madagascar, India, Sri Lanka, Australia) by matching conjugate magnetic anomalies and seafloor fabric from the Mozambique and Somali Basins, until we can no longer visually match the data in the two basins maintaining a single East Gondwana Unit (Figures 21a to 21c). We then allowed Madagascar-India-Sri Lanka to move free from Antarctica-Australia. This occurred around M15n as observed earlier by Davis *et al.*, (2016). Subsequently, we defined independent motions for Antarctica-Australia, and Madagascar-India-Sri Lanka using data from their individual basins (Figure 21c).

7.2 Valanginian-Barremian (M15 – M5) (~135Ma-125Ma)

The period corresponds to large-scale plate re-organisation across the world (Moulin and Aslanian, 2010). The Hauterivian/Valanginian boundary is marked by a reorganization in the Pacific Ocean, the first oceanic crust in the South Atlantic (Moulin *et al.*, 2010) and a number of remarkable magmatic events (e.g. Parana-Etendeka - Peate and Hawkesworth, 1996; Explora Wedge of Antarctica - Allsopp and Roddick, 1984; Rajmahal Traps - Vijaya and Bhattacharji, 2002; Alkaline volcanic intrusions within the Western Ophiolite Belt of Pakistan - Kazmin, 1991).

In the Indian Ocean, the period led to the formation of Curvier, Perth and Gascogne basins on the northwestern Australian margin (Veevers, 1988). On the Antarctic margin, it caused the separation between the Elan Bank and East Antarctica, leading to the formation of the Enderby Basin (Figure 21c-d). The Enderby Basin preserves the record of rifting between India–Sri Lanka and Antarctica-Australia. Despite several geophysical studies in the basin, definitive indicators of rifting age, spreading direction and rate, and clearly identifiable magnetic anomalies are lacking (Jokat *et al*., 2010; Golynsky *et al*., 2013), due to the Kerguelen Plateau and sedimentary cover in the basin. Gaina *et al*. (2007) and Gibbons *et al*. (2013), interpreted M-Series magnetic anomalies within the

Enderby Basin. Jokat *et al*. (2010) were unable to identify any M-Series magnetic anomalies to the west of the Enderby Basin, contending that the lack of clear magnetic anomalies in the west of the basin suggests that this part of the basin most likely opened during the Cretaceous Normal Superchron. However, recent deep seismic studies have interpreted seismic velocities in support of oceanic crust in the Princess Elizabeth Trough of the Enderby Basin (Leitchenkov *et al*., 2014). Davis *et al*. (2016) recently provide first order estimation of spreading rates during the early breakup of India and Antarctica in the Enderby Basin. They estimate full spreading rates of 7.5 km/Myr at 135 Ma (chron M15n), increasing to 15 km/Myr at 125 Ma (chron M4), and finally accelerating to 37.5 km/Myr at 120.6 Ma (chron M0r) between India and East Antarctica in the Princess Elizabeth Trough region.

The Early Cretaceous also corresponds, together with the Austral Segment of South Atlantic (Moulin et *al.*, 2010), to the beginning of the Patagonia movement and to the formation of the first oceanic crust in the South Natal Valley with a first magnetic anomaly around M12 or M10 (Goodlad *et al.*, 1982). This NE-SW movement together with the N-S movement of Antarctica-Australia block creates a triple junction, connected to the inception of the Maud Rise (MR) and the North Astrid Ridge (NAR) (Figure 21d-e).

The Marine transgression reached the southern end of the African block with the creation of the South Natal Valley and the opening of the South Atlantic Ocean.

In the Somali and Mozambique Basins, seafloor spreading continued with major marine transgression accompanied by intermittent regression (Walford *et al*., 2005). In the Mozambique Lowland and the North Natal Valley, the Maputo Formation, which represents the initial flooding of the shelf after the formation of the first oceanic crust offshore the two basins, was deposited.

7.3 Barremian-Coniacian (M5-C34) (~125-85Ma)

The Barremian/Aptian Boundary is marked by the inception of the Cretaceous Quiet Magnetic period and the start of a global plate reorganization, which both end during the Coniacian time. During the Turonian and Coniacian (95-85Ma), a serie of events occurred worldwide: the start of a spreading system in the Tasman Sea (Hayes and Ringis, 1973), the "crack " of the Farallon plate and the formation of the Chinook and Kula Plates and the Chinook Trough (Rea and Dixon, 1983), a major change in spreading direction in the Pacific Ocean (Searle *et al.*, 1993), the cessation of the spreading system of Osbourn Trough and the beginning of the spreading system between the Marye Byrd Land and the Campbell-Chatham Ridge, the breakup between Australia and Antarctica (Cande and Mutter, 1982) and more generally a major change in the configuration of the Indian Ocean (i.e., Sahabi, 1993),the North and Central Atlantic Oceans (Olivet *et al.*, 1984; Olivet, 1996) and worldwide (Scotese *et al*., 1988).

In the Indian Ocean, Madagascar-Greater India-Sri Lanka block stopped its southward drift from Africa and consequently seafloor spreading in the Somali Basin had stopped at M0 (Figure 21f). A low rate left-lateral strike-slip motion was initiated between India and Madagascar (Sahabi, 1993; Scotese *et al*., 1988). This rifting may have impacted the Sri Lanka microplate, which may have resulted in its separation from southern India between M0 to C34 (Sahabi *et al*., 1993). This could have led to further divergence between India-Sri Lanka and Antarctica-Australia and the creation of West Enderby Basin (Davis *et al*., 2016).

The Perth Abyssal Plain and the East Enderby Basin formed a continuous spreading system during the Aptian time (Gibbons *et al*., 2013), until a ridge jump initiated to commence seafloor spreading at Elan Bank and India after M0, in agreement with Jokat *et al*. (2010), who observed that pre-Cretaceous Normal Superchron (120.6 Ma) oceanic crust may not exist offshore the margin of Eastern India and the West Enderby Basin.

According to Frey *et al*. (2000), we initiate the beginning of the emplacement of the Kerguelen Plateau around 120Ma (Figure 21f). The Southern Kerguelen Plateau was initially attached to the Indian plate until a southward ridge jump was completed, attaching the plateau to East Antarctica. At Turonian time, the accretion in the Curvier, Perth and Gascogne basins stopped.

According to Eagles and Hoang (2013), transtensional deformation between Greater Indian and Madagascar resulting in seafloor spreading in the Mascarene basin initiated with a first magnetic anomaly at C34. The spreading resulted in a counter-clockwise rotation of Greater India (Kazmin, 1989), and consequently its boundary with the Neo-Tethys and African-Arabian crusts was affected the most, becoming the locus of convergence which led to the emplacement of the ophiolites in East Arabia and West Pakistan (Kazmin, 1991 and Gnos *et al*., 1997).

Dextral shear stress continued along Agulhas Falkland Fault zone (Ben-Avraham *et al*., 1997; Watkeys and Sokoutis, 1998, Baby, 2017), and widespread spreading in South Natal Valley and Southern Africa, creating Triple Junction between Africa, Antarctic and Falkland plates as the plates drifted. This may have created space for the emplacement of the South Mozambique Ridge, the Maud Rise, the Agulhas Plateau, and the northern part of the Astrid Ridge, which have been confirmed to have oceanic origin (Barrett, 1977; Gohl *et al*., 2011). The Agulhas Plateau and the Maud Rise align, lying north and south respectively around Ano34 (Leinweber and Jokat, 2012). The Mozambique Ridge and the Astrid Ridge also align to the east; according to Schlich *et al*. (1974) and Goslin, (1981), the position of these ridges with respect to anomaly 34 indicates that they are older than C34 (Figure 21g).

The alignment of the Madagascar plateau with the Del-Cano and Conrad plateaus in our model suggests that they may have been emplaced at the same time (Martin and Hartnady (1986), possibly due to excessive volcanism along the Southwest Indian Ridge as suggested by (Schlich *et al*., 1974 and Goslin, 1981; Goslin and Patriat, 1984) or due to hotspot activity between 90Ma-70Ma.

7.4 Comparison with previous evolution models

The trajectory in our model (dotted blue arrows in Figures 22 and 23) is compared to that proposed by Reeves *et al*., (2016), Gaina *et al*., (2013), Leinweber and Jokat (2012) and Sahabi (1993).

For the evolution of Madagascar (Figure 22), Reeves *et al*. (2016), as well as Davis et al. (2016) (Figure 3), start with an initial overlap of Madagascar on Africa. Leinweber and Jokat's model (2012) induces a WSW movement between 180Ma to 160Ma, producing an overlap before it begins a southward drift to its present position. Gaina *et al*. (2013) takes a more southeast drift throughout its evolution to its present position, while the model of Sahabi (1993) begins first with an initial southeastward movement and a subsequent southward drift.

Despite the difference in the positions of Madagascar (dotted colored lines) from the fit to the Barremian (~130 Ma), our evolution model may seem similar in direction to Reeves's model, which is the most continuous evolution model without sharp variation in direction. Nevertheless, Reeves's model describes a stop in the southwards movement of Madagascar between Berriasian and Barremian times (~140-130 Ma).

Gaina's model implies a different initial evolution, with a movement slightly eastern, due to a more north-south position of Madagascar at fit time. The timing is nevertheless different as the movement of Madagascar starts later, at Bajocian (~170 Ma) almost ending at Barremian (~130 Ma). During the evolution, Madagascar is situated eastward to our positions (dotted colored lines).

Many more differences are observed with Leinweber and Jokat model's (2012), which describes a zigzag evolution implying a compressive event until the Oxfordian (~160 Ma).

A less pronounced and inverse zigzag is described by Sahabi's Model (1993), as the fit position of Madagascar is more to the north and less north-south oriented. Since Berriasian (~140Ma), the positions of Madagascar are very similar to our model.

For the evolution between Antarctica and Africa (Figure 23) three models (Leinweber *et al.,* 2012; Gaina *et al.,* 2013; Reeves *et al.*, 2016) opted more or less for an overlap of Antarctica on Mozambique Lowland. This hypothesis implies a bend (and even a zig-zag for Gaina) in the Antarctica motion. Note furthermore that the Antarctica plate crosses the fracture zone, which prolongs the Limpopo strike-slip margin. The only model in coherence with the new geophysical date in Mozambique Lowland and North Natal Valley is that of Sahabi (1993). It differs slightly with our model as our fit is less tight due to the fact that his fit overlaps the Beira High.

8. Conclusion

In this study, we analysed current reconstruction models of the Indian Ocean to examine their consequences and underlying reasons, in the light of past and new data. We have specifically undertaken the study of onshore and offshore geological and geophysical data published and newly acquired within the framework of the PAMELA project. These models present a number of gaps, overlaps and misfits of major structural and Cratonic bodies, and raise critical scientific questions. We therefore presented a new kinematic model of Gondwana's initial fit and evolution, taking into account these observations. Our model is coherent and respects current knowledge on major structures in the Indian Ocean. It shows the full extent of major cratonic blocks and a good juxtaposition of key structures and basins constituting Gondwana.

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AUTHOR CONTRIBUTIONS

D.A. and M.M. designed this study. J.O.T. made the kinematic and geological compilations with the help of M.M. and D.A., for geodynamics, F.G. and PdC for basement and the stratigraphy charts. J.O.T., with the help of M.M. and D.A., calculated and draw the final kinematic reconstructions and evolution. All authors contributed to the final submitted manuscript.

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Table 1: INITIAL FIT POLES.

Tectonic Plate (All motions relative to Africa	Latitude	Longitude	Rotation

Austral)			
Antarctica	8.969426	151.6038	-58.75505
Madagascar	9.384853	117.2845	-15.40567
India	31.31943	38.96307	-58.86290
Australia	23.67146	119.8226	-54.90728
Sri Lanka	17.65087	50.91434	-86.33724
Patagonia-Falkland	46.92559	-33.09283	57.66492
Seychelles	6.548114	57.69930	-52.07016

See Moulin et al., (2010) for the poles of Africa Nubia, Africa West, Benue block, Guyana, NE Brazil, Tucano, São Francisco, Santos, Plata, Argentina, and Salado.

Table 2: Poles Antarctica-Africa

Ano34	-1.3	-34.7	17.78	Bernard et al. (2005)
M0	11.72991	154.0759	-42.51146	This study
M5n	12.68688	154.0827	-44.66053	This study
M10r	9.705075	152.8902	-46.33414	This study
M15n	9.864203	153.7544	-50.71872	This study
M22n	8.271569	152.2943	-53.09270	This study
M25n	8.428259	152.0446	-55.43329	This study

Table 3: Poles Madagascar-Africa

Age	Latitude	Longitude	Rotation	Source
M0r	0.000	0.000	0.000	M0r
M5n	8.683980	-107.8003	5.789815	This study
M10r	3.488152	-98.77951	6.404223	This study
M15n	4.675859	97.03268	-8.123477	This study

M22n	2.188300	102.7732	-10.97189	This study
M25n	5.161909	110.0051	-12.69742	This study

Table 4: Poles India-Africa

Ano34	22.4300	24.9600	-53.6300	Eagles and Hoang (2013).
M0r	22.22783	24.40480	-56.71661	This study
M5n	22.16459	29.60182	-60.14409	This study
M10r	23.17356	30.41119	-60.07137	This study
M15n	25.46677	32.16216	-59.68924	This study
M22n	26.59191	35.30000	-59.83694	This study
M25n	28.44201	36.86446	-59.31655	This study

Table 5: Poles Australia-Africa

Ano34	16.90723	75.47579	-27.48594	This study
M0	24.73430	107.5313	-41.06655	This study
M5n	26.15952	109.5644	-42.60602	This study
M10r	23.21838	111.0177	-44.40272	This study
M15n	24.13406	115.6568	-47.28139	This study
M22n	22.52906	116.5607	-49.91948	This study
M25n	22.88478	118.0439	-51.93749	This study

Table 6: Poles Sri Lanka-Africa

M0r	10.11700	42.55943	-81.32627	This study
M5n	10.18472	45.66046	-85.58115	This study
M10r	10.99839	46.09781	-85.72527	This study

M15n	12.82913	47.08052	-85.77724	This study
M22n	13.94529	48.91399	-86.72331	This study
M25n	15.41446	49.81841	-86.50547	This study

Table 7: Poles Seychelles-Africa

M0r	2.905783	-136.6054	45.91607	This study
M5n	2.311616	-133.3757	51.06846	This study
M10r	1.266099	-132.3603	51.14625	This study
M15n	1.030455	49.95525	-51.10443	This study
M22n	2.044542	52.97449	-52.31302	This study
M25n	3.771343	55.01324	-52.15144	This study

Figures

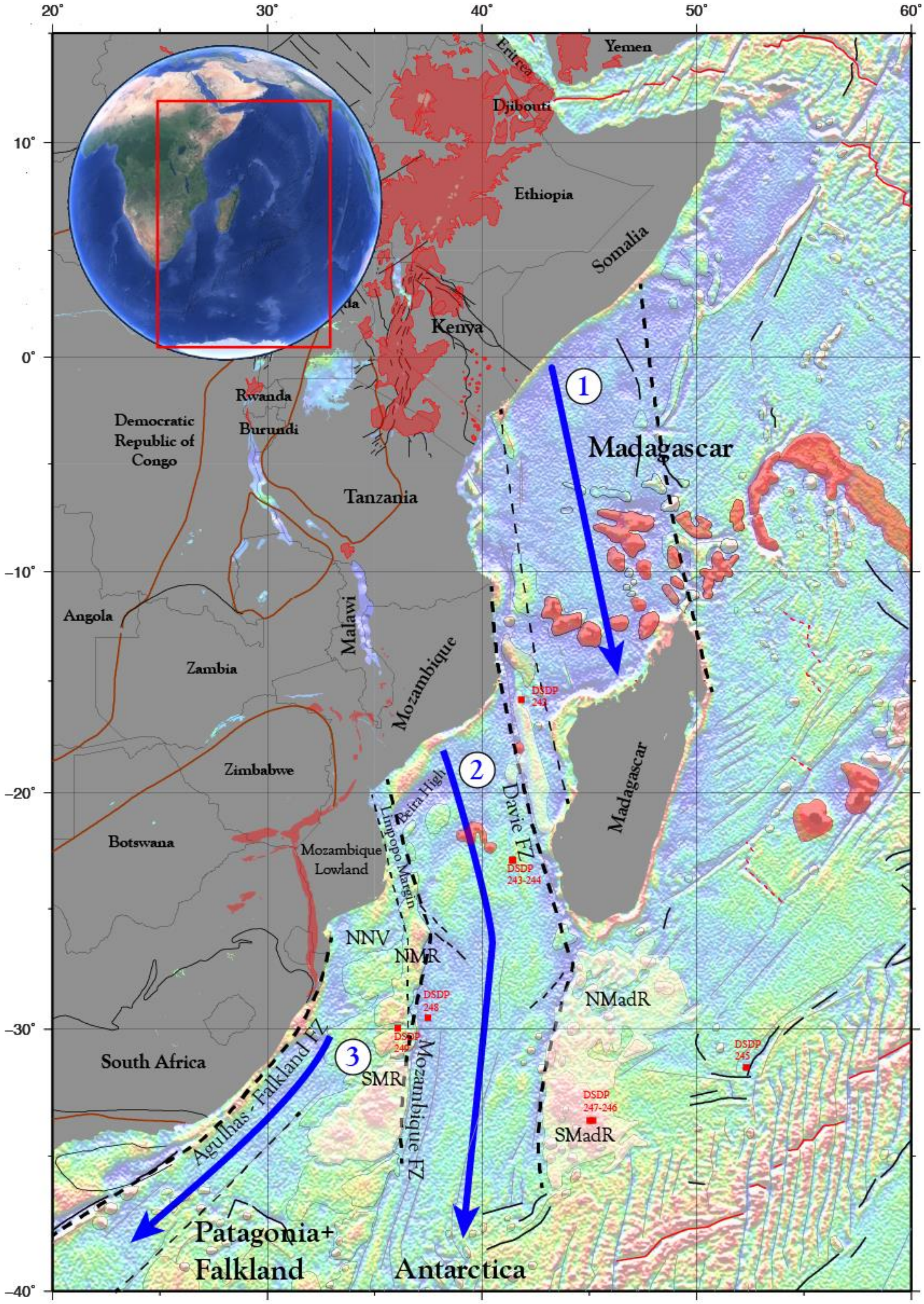

Figure 1 - Thompson et al.

Figure 1: Free-air satellite-derived gravity anomaly of the Mozambique Channel by Sandwell *et al.*, (2014), showing the complexity and segmentation of the East African margin. Segment 1 and 2 correspond respectively to the movement of the Madagascar and Antarctica tectonic plates, and the segment 3 corresponds to a later event involving the drifting of the Falkland and Patagonian plates. NNV= North Natal Valley, NMR= North Mozambique Ridge; SMR= South Mozambique Ridge; NMadR= North Madagascar Ridge; SMadR= South Madagascar Ridge. In red= Volcanism without distinction about the age (Mercator projection)

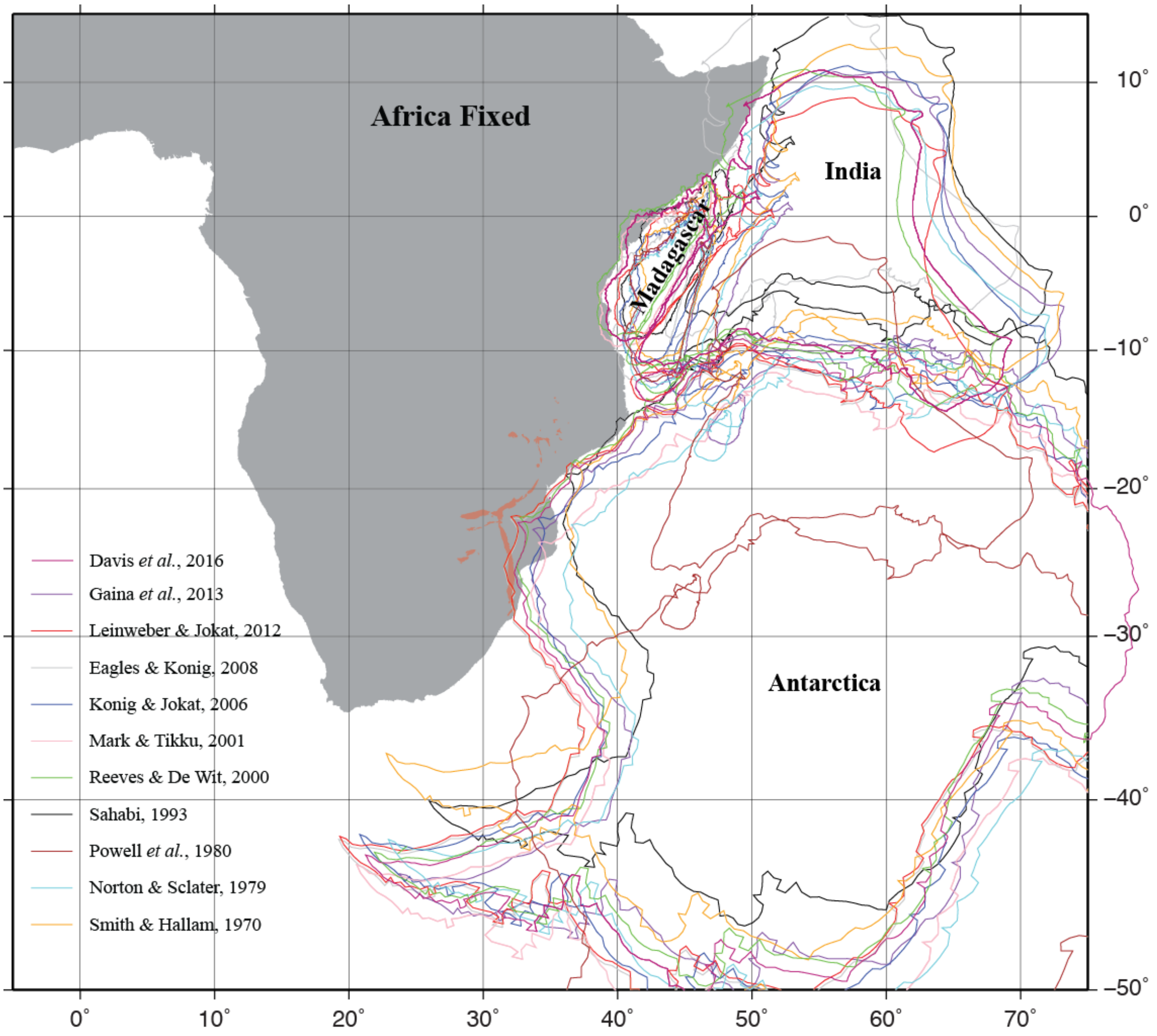

Figure 2 - **Thompson et al.**

Figure 2: Selected Gondwana reconstructions models, respect to Africa, by Smith and Hallam (1970) Norton and Sclater (1979), Sahabi (1993), Reeves and de Wit (2000), Marks and Tikku (2001), Konig and Jokat (2006), Eagles and Konig (2008), Leinweber *et al.* (2012), Gaina *et al.* (2013), Davis *et al.* (2016), highlighting the large variations within the initial proposed fits. The models present different positions for the plates, and result in overlaps, gaps, latitudinal, and angular differences. (Mercator projection).

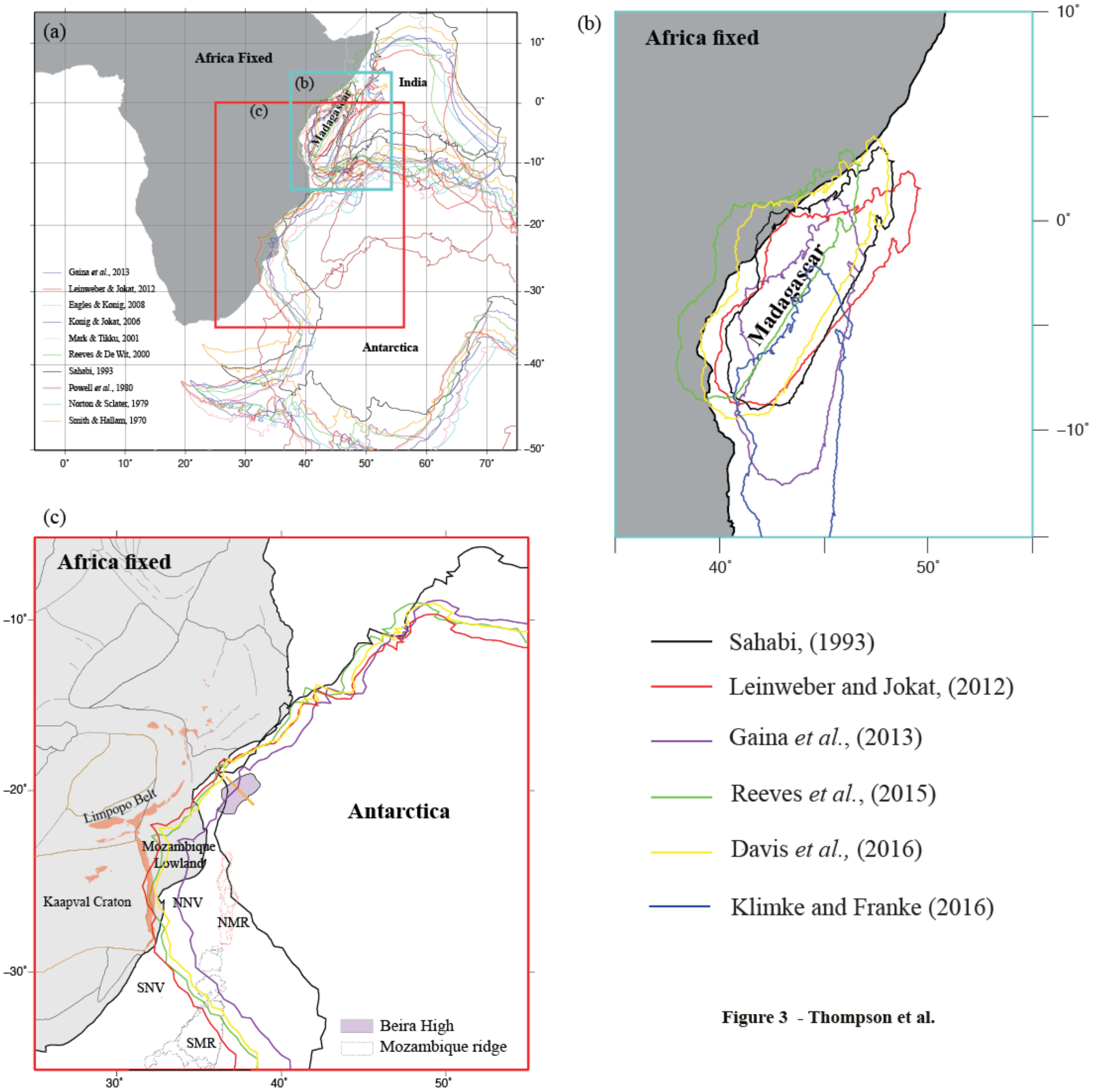

Figure 3: Map showing comparing the reconstruction models of Sahabi (1993), Leinweber and Jokat, (2012), Gaina *et al.*, (2013), Reeves *et al.*, (2015), Davis et al., (2016) and Klimke & Franke (2016) at the same scales. Notice the large differences in the placement of the plates in terms of latitude and angle. With regard to the fit between Africa and Antarctica, notice the overlap of Antarctica on the Mozambique Lowland in (Davis *et al.*, 2016, Reeves *et al.*, 2015; Gaina *et al.*, 2013 and Leinweber and Jokat, 2012). The North Mozambique Ridge (In yellow) was found during recent expedition in the Mozambique Basin of MOZ3-5 to consist mainly of sediments on a thinned continental crust (Leprêtre *et al.*, 2017; Moulin *et al.*, submitted). The Southern Mozambique Ridge (in black) maybe composed of volcanics (Gohl *et al.*, 2011) possibly emplaced at a triple junction. (Mercator projection)

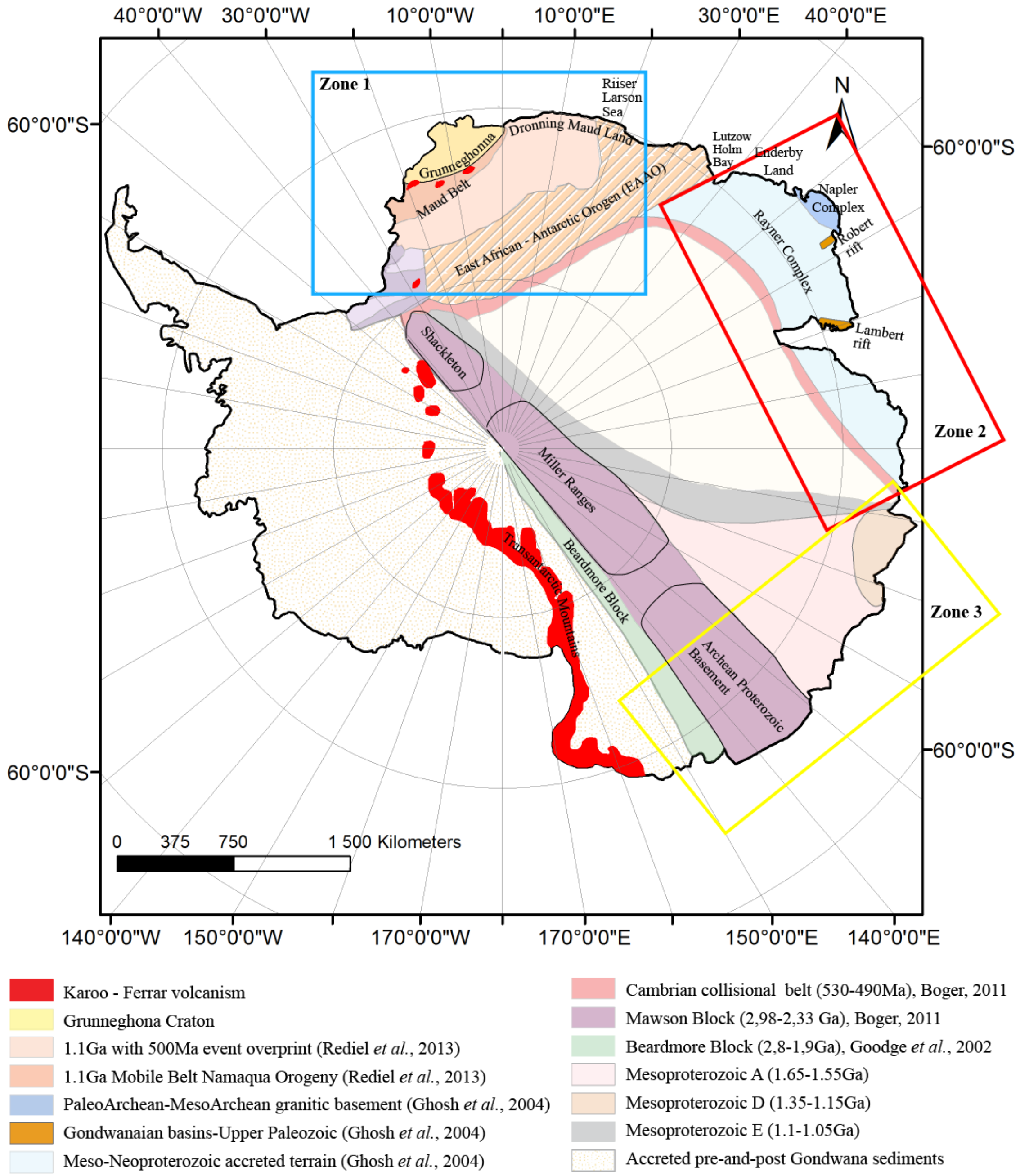

Figure 4 - Thompson et al.

Figure 4: Basement geology of Antarctica compiled from (Kelly *et al.*, 2002; Ghosh *et al.*, 2004; Boger, 2011; Rediel *et al.*, 2013: – see Plate 1 supplementary material). Based on geochronological properties and similar orogenic history, the area marked Zone 1 (Blue rectangle) is related to the Kaapval craton of Southern Africa, Zone 2 (Red rectangle) is related to the Eastern Ghats craton of Eastern India, and Zone 3 (Yellow rectangle) is related to the Australian plate. The trace of the Beardmore, Mawson, Mesoproterozoic A, D, E, and the accreted pre and post Gondwana sediments in Antarctica and Australia are after Boger (2011). World Geodectic System 1984, same as figures 4-9.

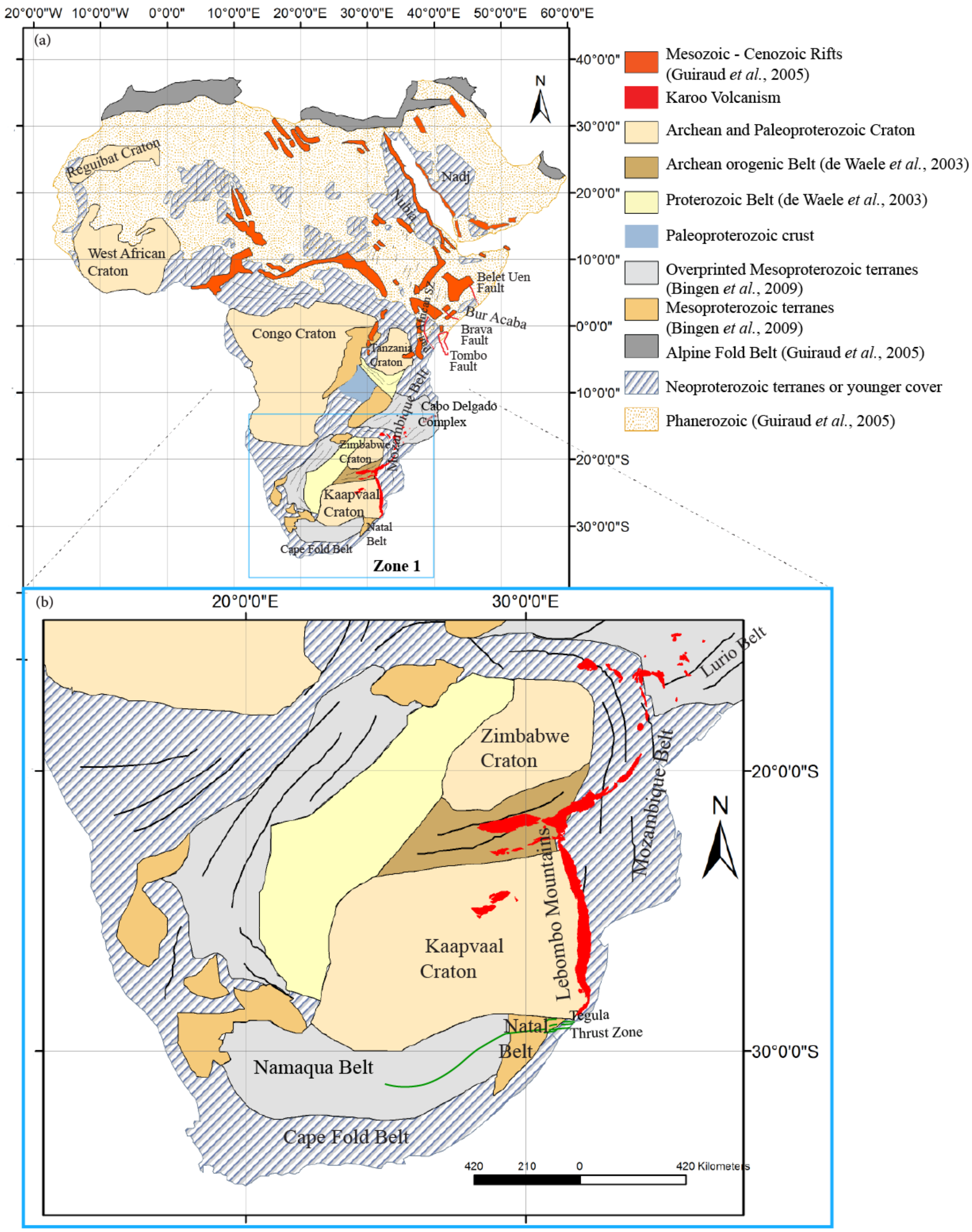

Figure 5 - Thompson et al.

Figure 5: (a) Geological map of Africa compiled from (Daly *et al.*, 1989; de Waele *et al.*, 2003; Guiraud *et al.*, 2005; Jacobs *et al.*, 2008; Bigen *et al.*, 2009; Rekha *et al.*, 2014; Foster *et al.*, 2015). The zone 1 (blue rectangle Figure 67) marks a domain of similar geochronological properties with Antarctica. (b) Zoom on Figure 5a showing the domain of shared geological history with the Antarctica plate. The Archean Kaapvaal Craton bears similar geochemical signatures to Archean Grunnehogna Craton, most likely forming a single craton. The Namaqua-Natal belt formed during the Namaquan Orogeny (1.1-10Ga), and is regarded as an extension of the Mesoproterozoic Maud Belt (1.1Ga) in Antarctica.

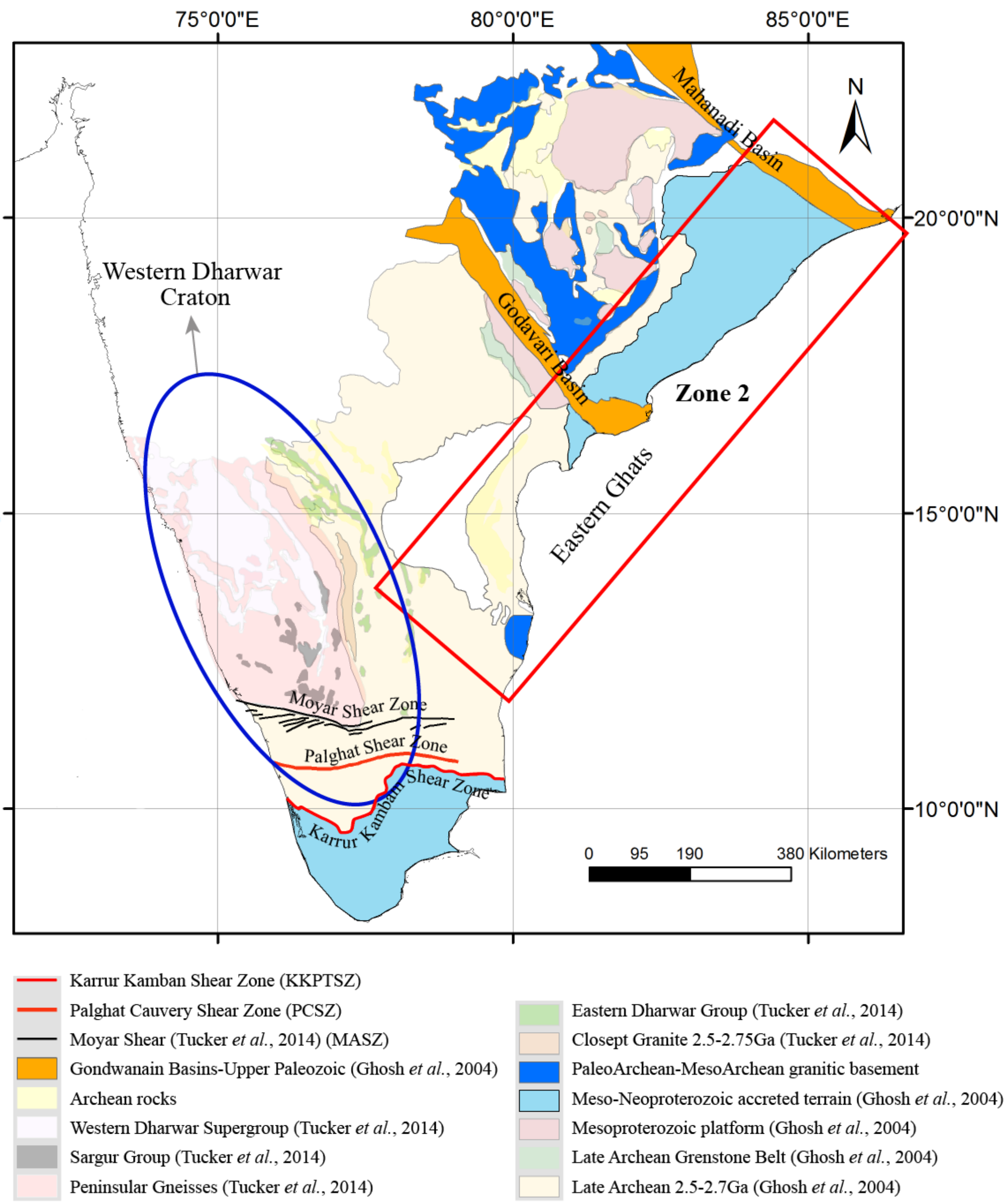

Figure 6 - Thompson et al.

Figure 6: Geology of India basement compiled from (Tucker *et al.*, 2014; Rajaprian *et al.*, 2014; Dasgupta *et al.*, 2013; Ghosh *et al.*, 2004; and www.portal.gsi.gov.in/portal 11/07/2016). The marked area zone 2 (Figure 4) indicates area of similar geological similarities with Antarctica. Rocks of the Ghats share similar geochronological properties with rocks of Enderby Land in East Antarctica. The Dharwar Craton of India shares similar geochemical and geochronological properties with the Archean rocks of eastern Madagascar.

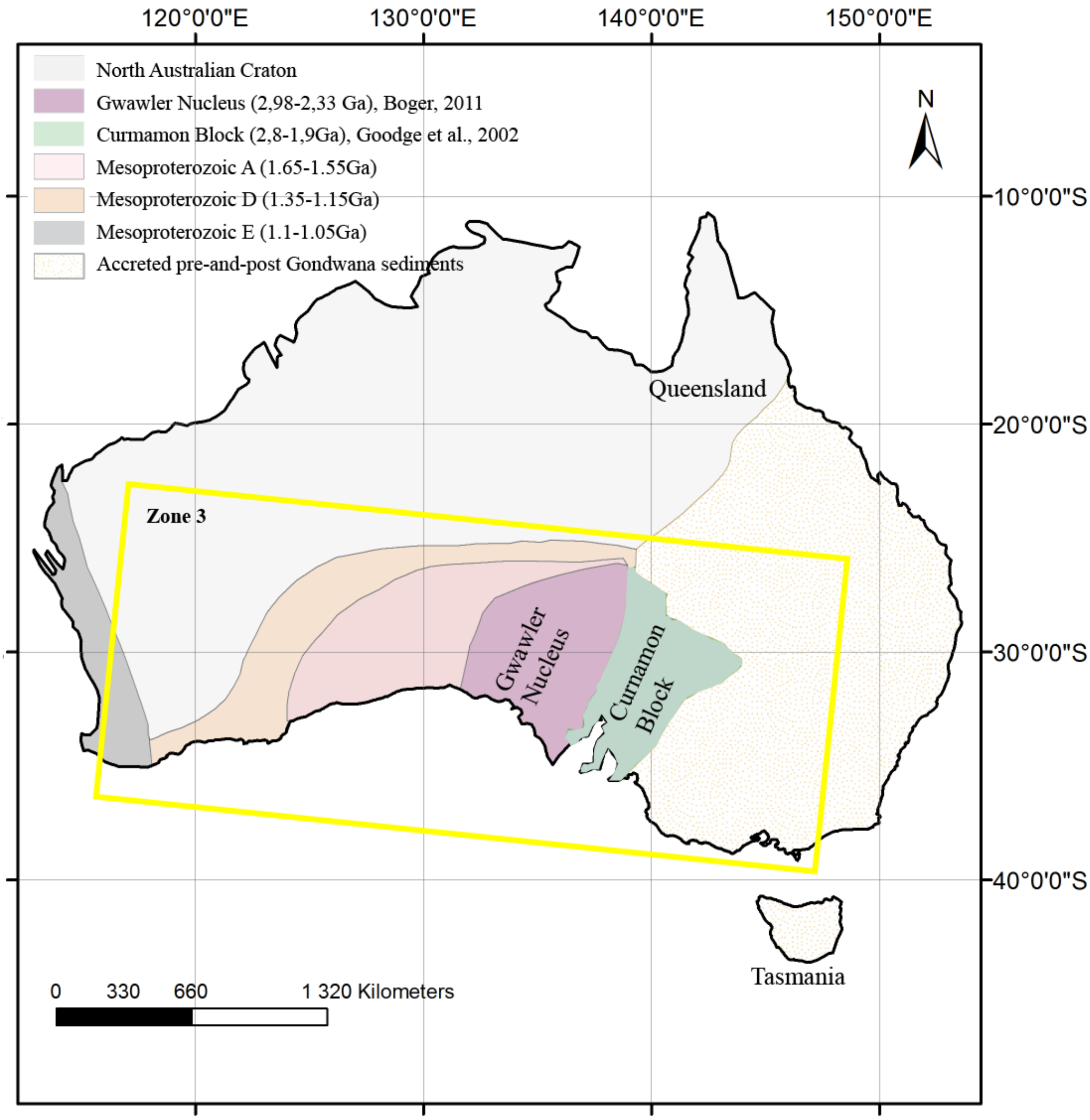

Figure 7 - Thompson et al.

Figure 7: Basement geology of the Australian modified (after Borg and DePaolo, 1991 and Boger, 2011). Zone 3 indicates area of sheared geological similarities with Antarctica. The Mawson and Beadmore blocks of Antarctica continue into the Gawler and Curnamon blocks in Antarctica respectively, bearing similar geochemical and geochronologically characteristics (Boger, 2011).

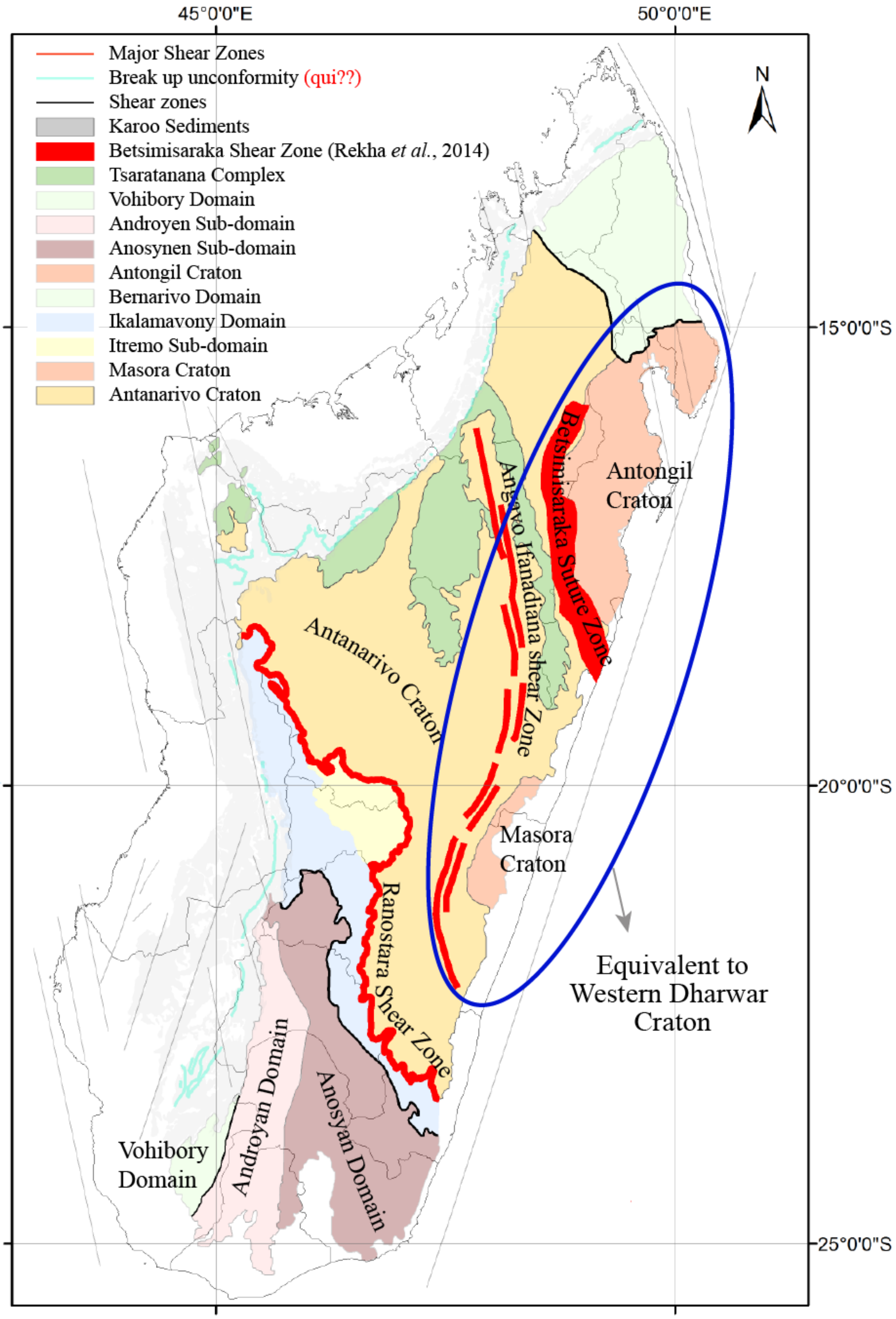

Figure 8 - Thompson et al.

Figure 8: Geology of Madagascar compiled from (Tucker *et al.*, 2014 ; Rekha *et al.*, 2014 ; Rasoamalala *et al.*, 2014 ; Nessen *et al.*, 1988 ; Courrier and Lafont, 1987; Besairie and Collignon, 1972). The Western Dharwar craton Of Madagascar shares similar geochemical and geochronological properties with the Dharwar craton in India. The Batsimisaraka shear zone in Rekha *et al.*, 2014, is argued by Tucker *et al.*, 2014 not to be evident.

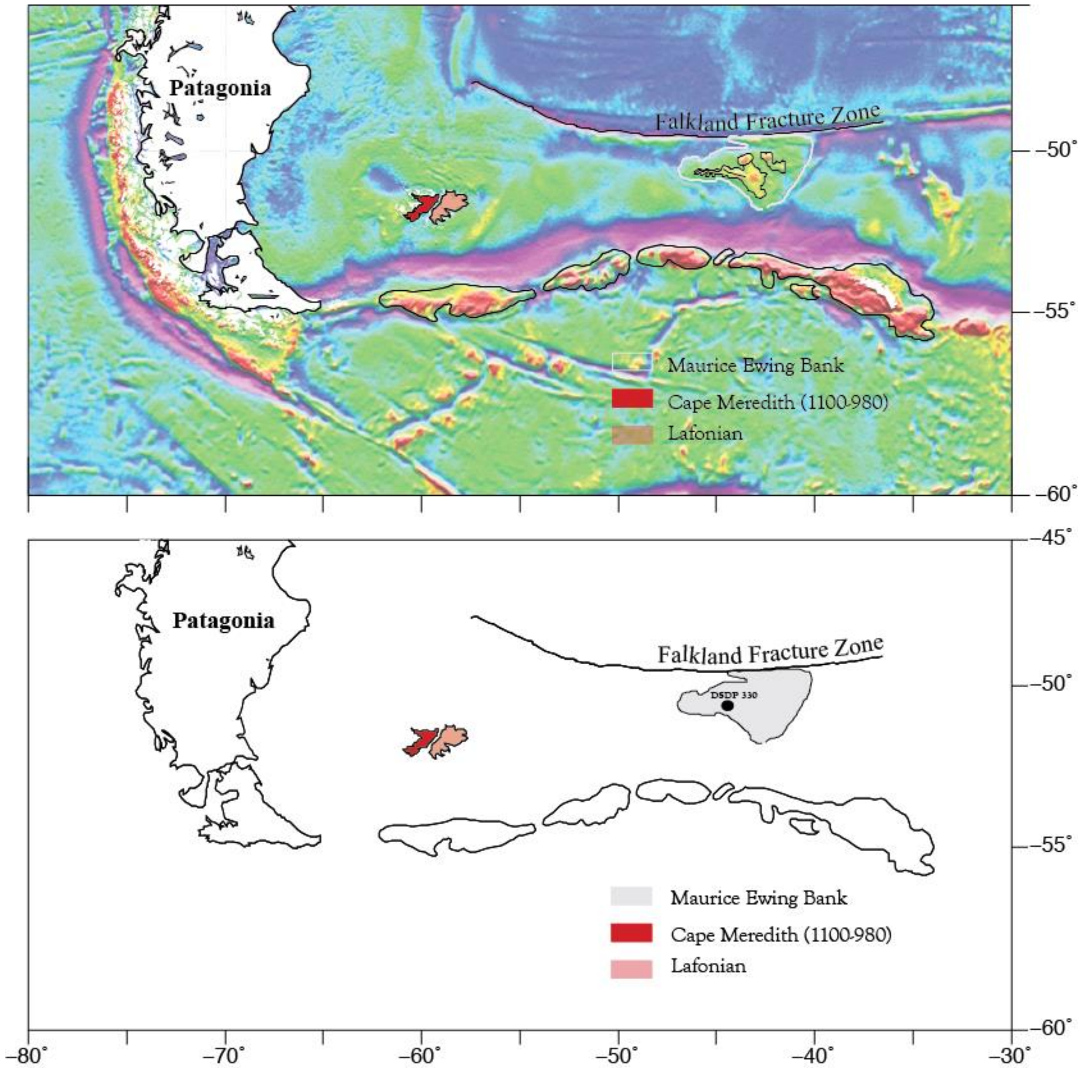

Figure 9 - **Thompson et al.**

Figure 9: Geological map of the Falkland Plateau compiled from (Lock, 1978; Martin *et al.*, 1982; Marshall, 1994; Curtis and Hyam, 1998). DSDP Hole 330 was bottomed in Precambrian rocks (554± 66Ma, Lorenzo and Mutter, 1988) correlative with the Pan-African ~650-500Ma Cape basement of Southern Africa.

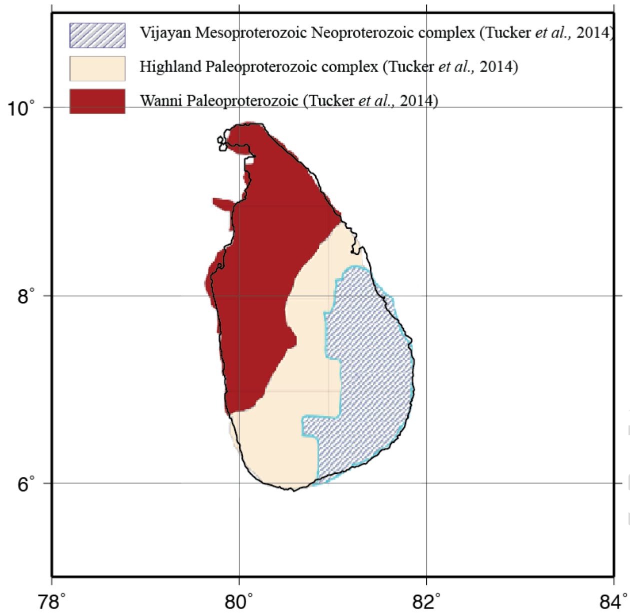

Figure 10 - Thompson et al.

Figure 10: Basement geology map of Sri Lanka (modified after Kröner *et al.*, 2003; Bingen *et al.*, 2009; Kelly *et al.*, 2002; and Tucker *et al.*, 2014

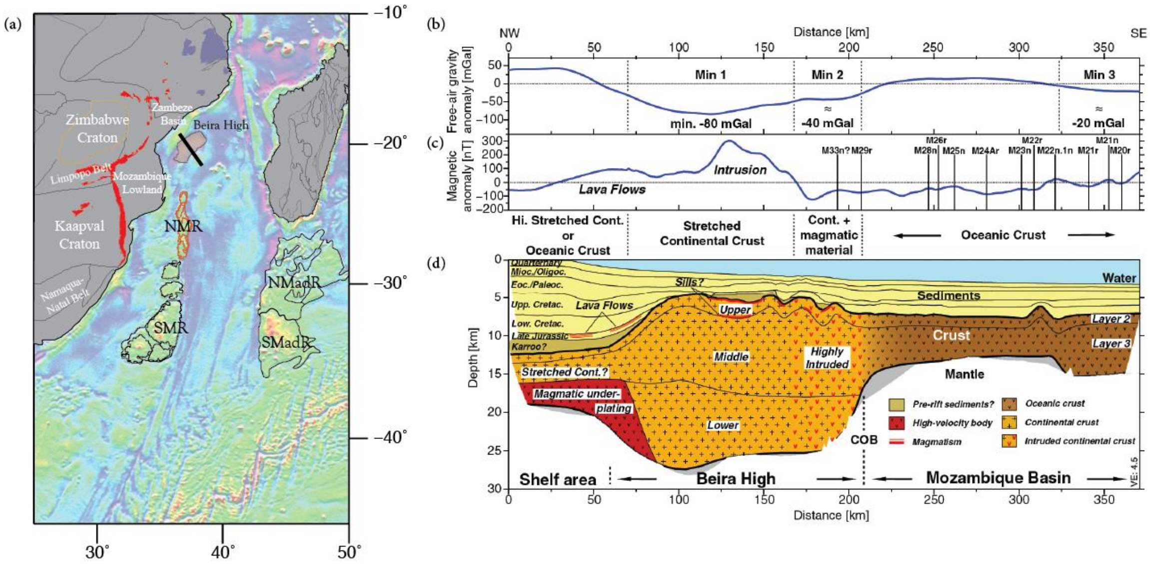

Figure 11 - Thompson et al.

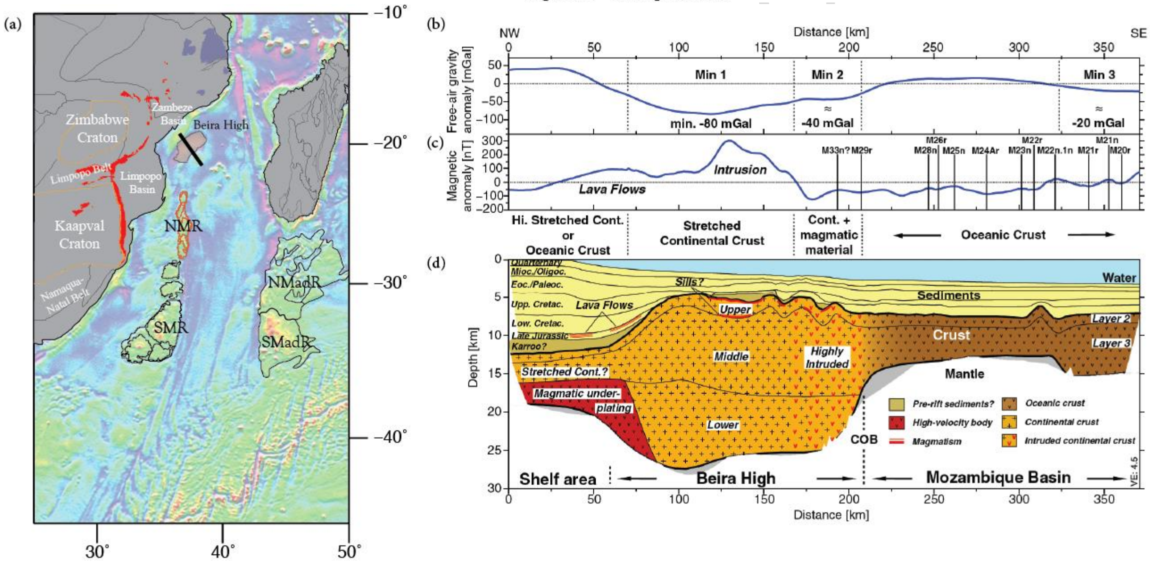

Figure 11 - Thompson et al.

Figure 11: (a) Free-air satellite-derived gravity anomaly of the Mozambique Channel by Sandwell *et al.,* (2014) (Mercator projection). The black line across the Beira High shows the location of the seismic refraction profile 2014001014 of Mueller *et al.,* (2016). The north Mozambique Ridge (in red) discovered in recent expedition in the Mozambique Basin of MOZ3-5 to be compose mainly of sediment on a thinned continental crust (Leprêtre *et al.,* 2017; Moulin *et al.,* submitted). The southern Mozambique Ridge (in black) maybe composed of volcanics (Gohl *et al.,* 2011) possibly emplaced at a triple junction. (b) The free-air gravity anomaly along the profile (c) Magnetic anomaly along the profile. The magnetic anomalies were from Leinweber and Jokat (2012). (d) Wide-angle seismic profile 2014001014 seismic across the Beira High and the Zambezi depression by Mueller *et al.,* (2016). They interpreted the Beira High to be of continental origin, and that the Zambezi depression consists of stretched continental crust.

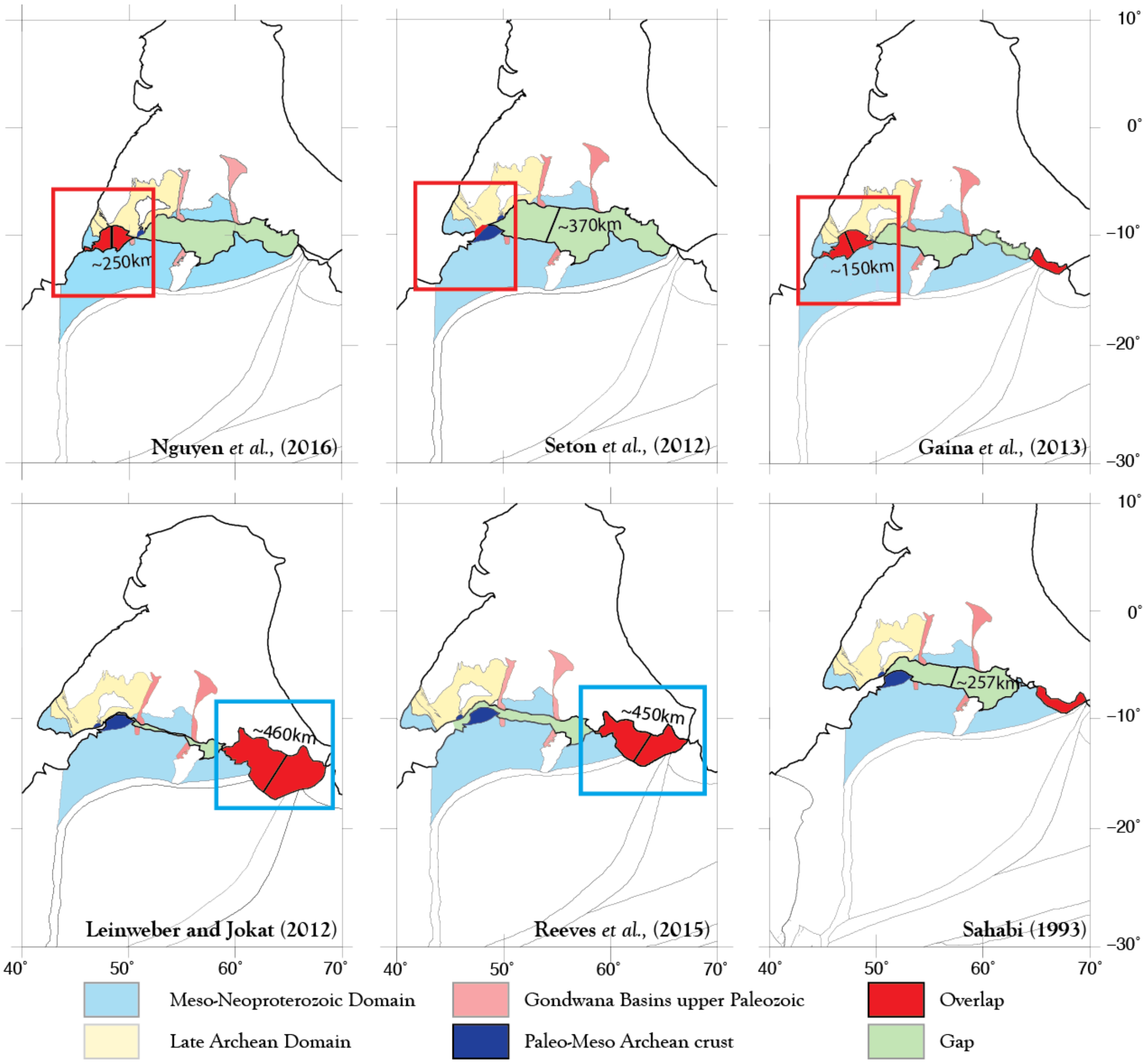

Figure 12 - **Thompson et al.**

Figure 12: Comparism (zoom) of India and Antarctica with reference to Africa for the models of Nguyen *et al.* (2016), Reeves *et al.* (2015), Gaina *et al.* (2013), Leinweber and Jokat (2012), Seton *et al.* (2012) and Sahabi (1993). The models of Nguyen *et al.* (2016), Gaina *et al.* (2013) and Seton *et al.* (2012) result in misalignment of Archean rocks of the Napier complex and the Ghat craton, and the Gondwanaian rifts basins. Reeves *et al.* (2015), Leinweber and Jokat (2012) and Sahabi (1993), on the other hand result in a perfect alignment of Archean rocks of the Napier complex and the Ghat craton, and Gondwana rifts basins. Notice the large overlaps in Nguyen *et al.* (2016), Reeves *et al.* (2015), Gaina *et al.* (2013) and Leinweber and Jokat (2012). (Mercator projection).

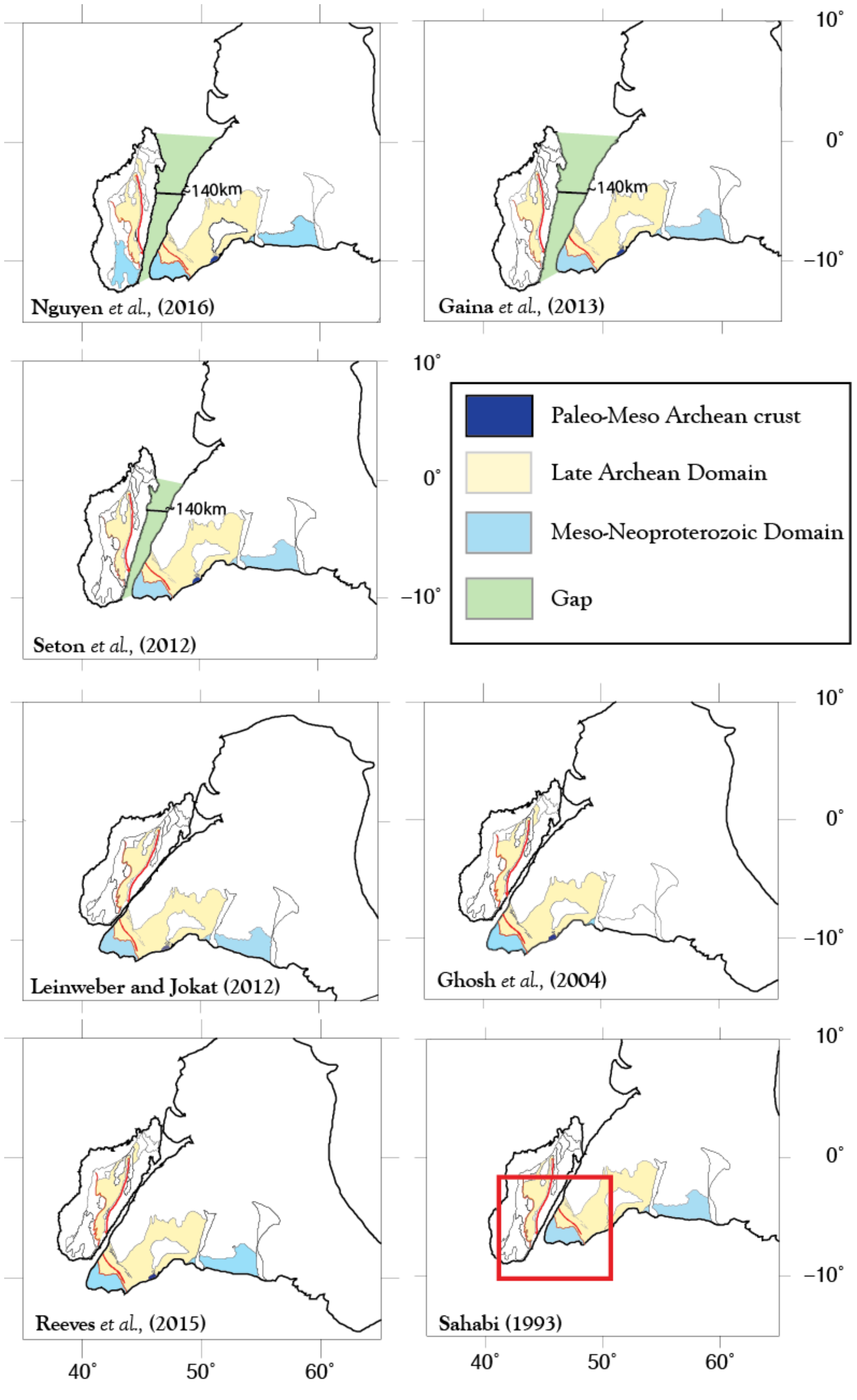

Figure 13 - **Thompson et al.**

Figure 13: Comparing reconstruction of Madagascar and India with reference to Africa in Nguyen *et al.* (2016), Reeves *et al.* (2015), Gaina *et al.* (2013), Leinweber and Jokat (2012), Seton *et al.* (2012), and Sahabi (1993). In Reeves *et al.* (2015) and Leinweber and Jokat (2012), the Agavo Ifanadiana shear zone is aligned with the Moyar shear zone, resulting in Mesoproterozoic rocks of Ikalamavony in Madagascar fitted with Archean rocks Dharwar craton in India. Nguyen *et al.* (2016), Gaina *et al.* (2013) and Seton *et al.* (2012), on the other hand results in about ~140km gap between India and Madagascar, and fits Mesoproterozoic rocks to Archean rocks between the two plates. Sahabi (1993) fits the Moyar shear zone to the Betsimisaraka shear, a structure argued by Tucker et al. (2014) to be non-evident, which produces a much North-West position for the Indian plate (red box),. (Mercator projection).

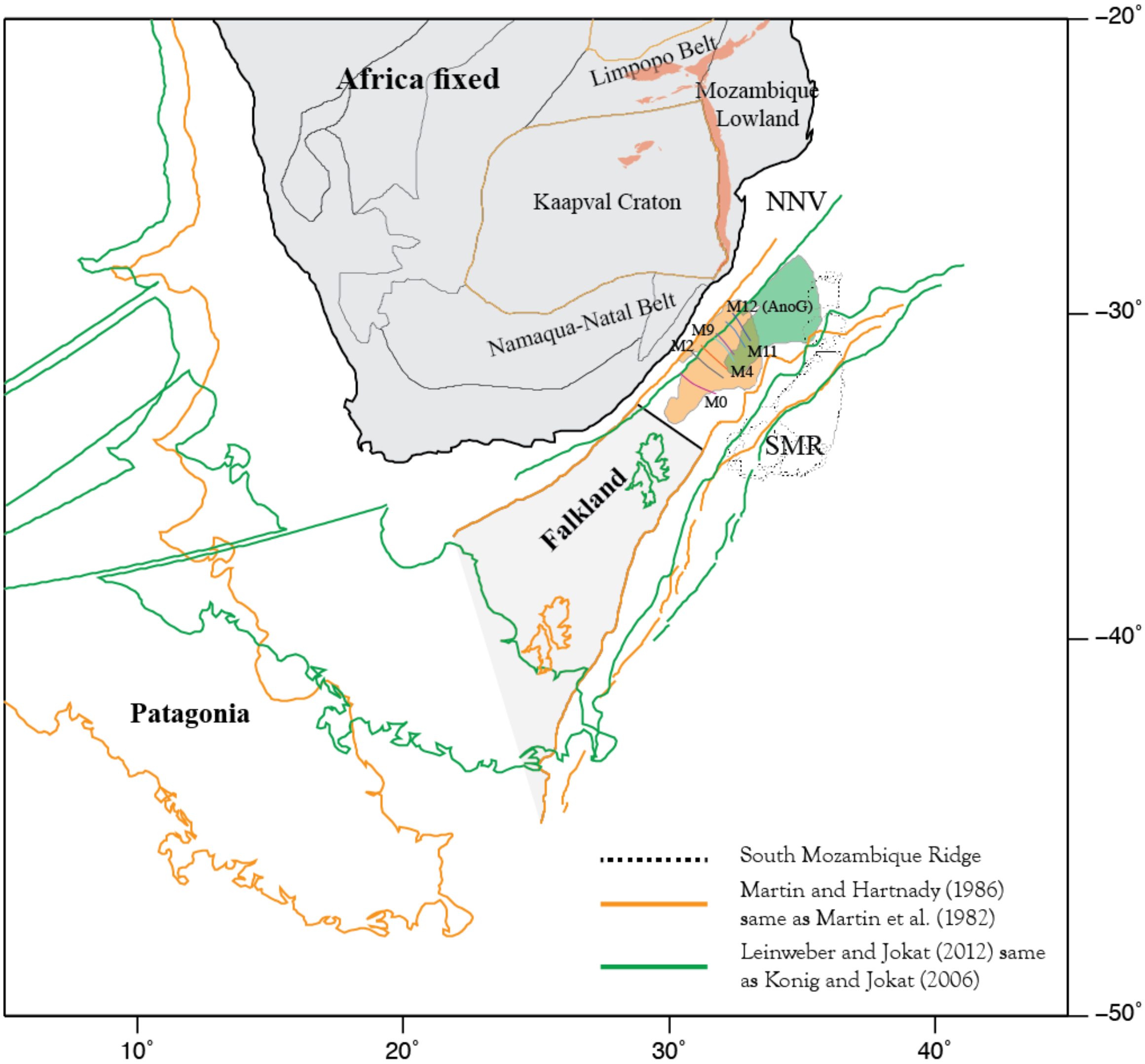

Figure 14 - Thompson et al.

Figure 14: Comparing the proposed fit for the Falkland-Patagonia in the reconstruction of Martin and Hartnady (1986) and Martin et al. 1982, and the models Leinweber and Jokat (2012) and Konig and Jokat (2006) relative to African plate. Notice Leinweber and Jokat (2012) and Konig and Jokat (2006) (orange) significantly overlap the North Natal Valley, which is underlain by continental crust (Lepretre *et al.*, 2017). SMR= South Mozambique Ridge.

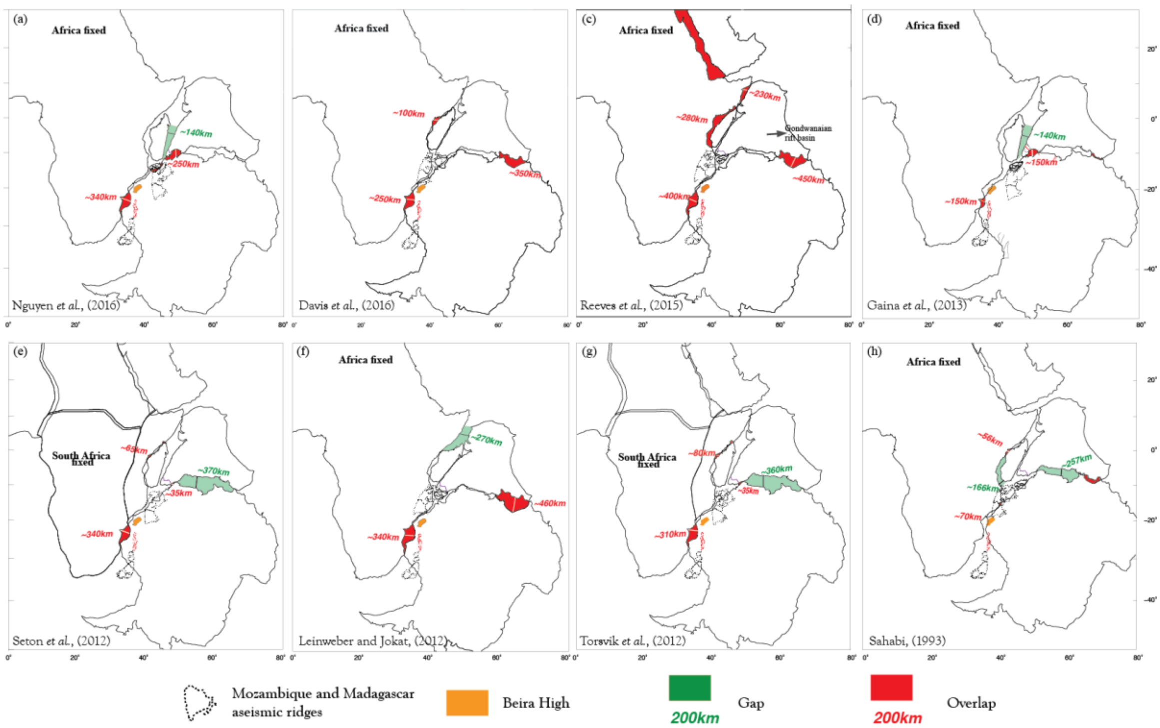

Figure 15 - Thompson et al.

Figure 15: Comparing the kinematic models of Nguyen *et al.* (2016), Davis *et al.* (2016), Reeves *et al.* (2015), Gaina *et al.* (2013), Seton *et al.* (2012), Leinweber and Jokat (2012), Torsvik *et al.* (2012) and Sahabi (1993). Leinweber and Jokat (2012), Reeves *et al.* (2015), Davis *et al.* (2016) are modelled after the geochronological studies of Ghosh *et al.* 2004. In these models, the Agavo Ifanadiana shear zone (Madagascar) is aligned with the Moyar shear zone (West India). This results in overlap between India and Antarctica. Gaina *et al.* (2013) and Sahabi (1993) on the other hand, fit the Betsimisaraka shear zone to the Moyar shear zone avoiding the overlap, but inaccurately fit Mesoproterozoic rocks to Archean rocks. The models of Seton *et al.* (2012) and Torsvik *et al.* (2012) result in misalignment of Archean rocks of the Napier complex (Antarctica) and the Eastern Ghat craton (East India), and the conjugate Gondwanaian rifts basins. Sahabi (1993) and Davis *et al.* (2016), on the other hand presents alignment of Archean rocks of the Napier complex and the Ghat shield and a good alignment of the Gondwanian rifts basins. (Mercator projection).

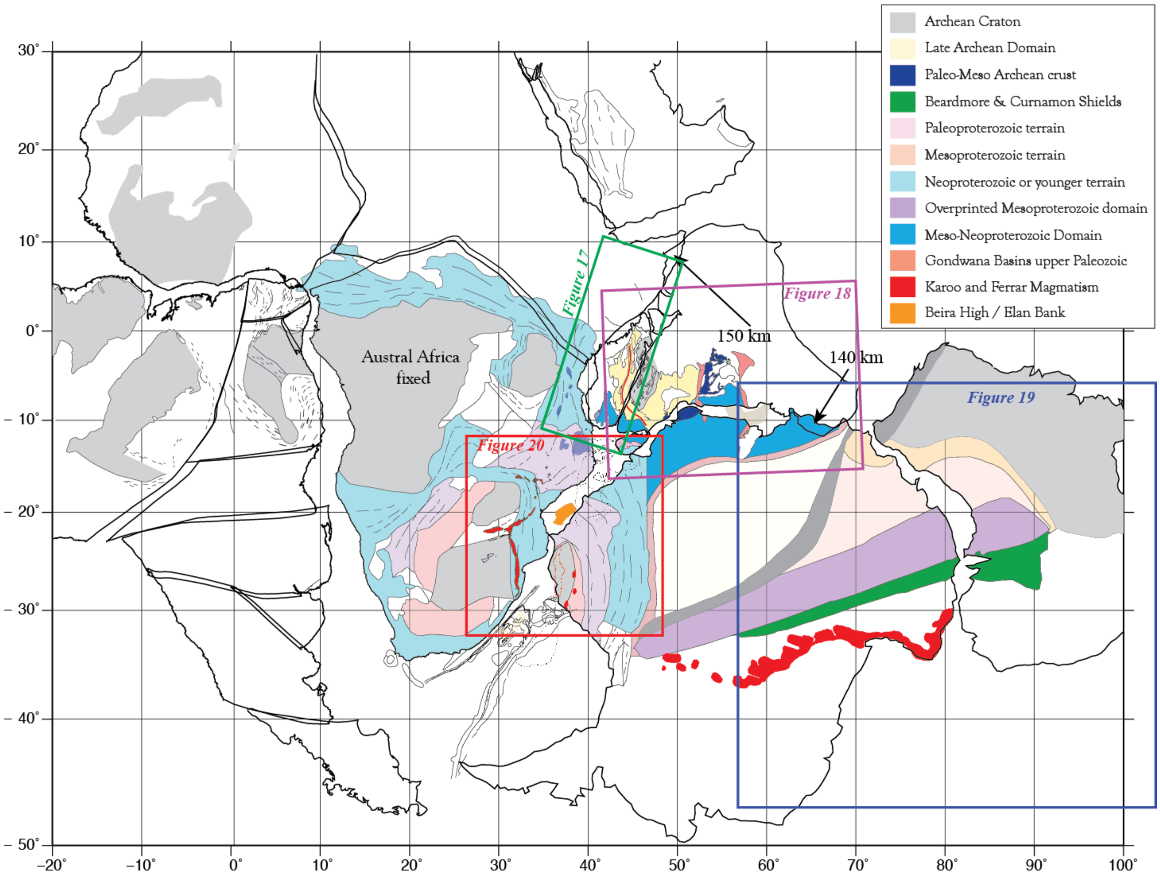

Figure 16 - Thompson et al.

Figure 16: Our proposed initial fit of Gondwana. This new model shows the full extent of the Dharwar craton traced from the India plate into Madagascar and possibly into the Bur Acaba of Africa and beyond. It permits a very good alignment of the Beardmore and Mawson cratons in Antarctica and Australia, and allows a good trace of Mesoproterozoic rocks of Antarctica and Australia to be traced into each other. It also grants a perfect alignment of Archean rocks of the Napier complex and the Ghat craton, and a good alignment of Gondwana rifts basins. (Mercator projection) The gap is filled, as the figure of our model shows, by the northern Madagascar part, supposed to be continental, the Beira High, the Natal Valley.

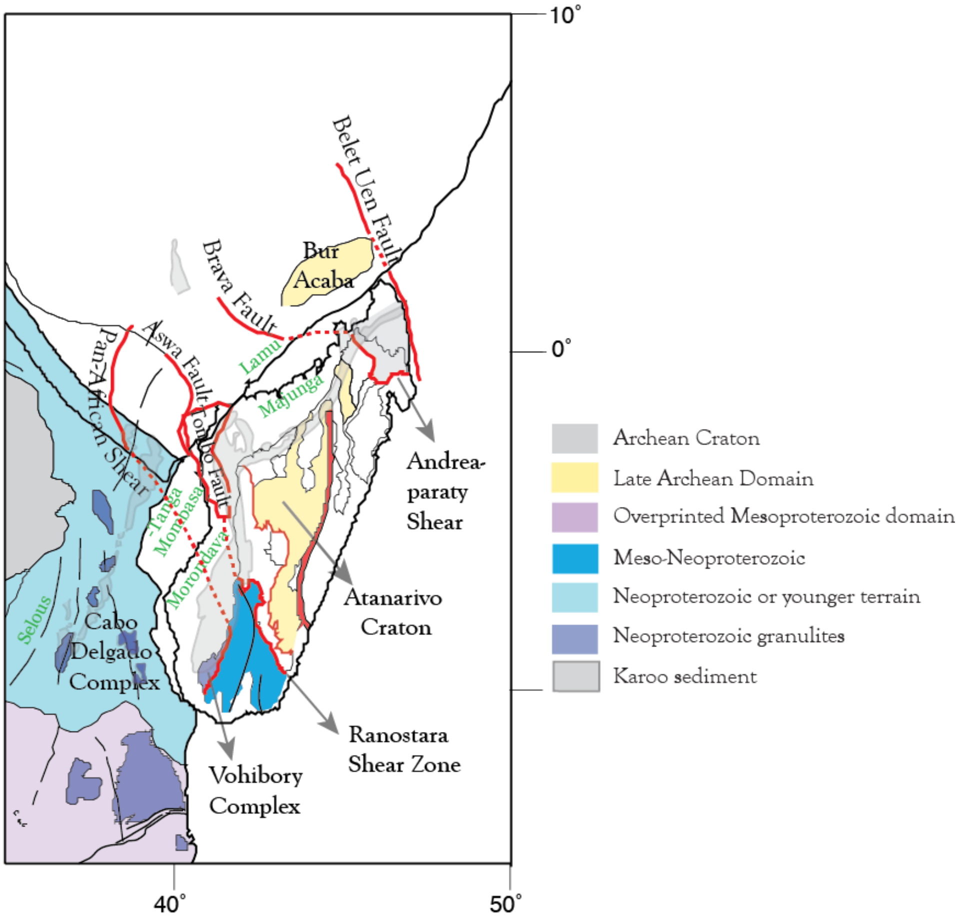

Figure 17 - Thompson et al.

Figure 17: Map showing our reconstruction of Madagascar with respect to Africa. The continuation of the Vohibory Pan-African shear zone to the Pan-African shear zone in Tanzania (de Wit *et al.*, 2001; Reeves and de Wit, 2000), the Ranotsara shear zone is linked to the Tombo faults, which we propose may continue into the Aswa shear zone in Uganda (Collins & Windley, 2002; Reeves, 2014), the Brava fault in Kenya continues with the Andreaparaty shear zone in Madagascar, and the Belet Uen fault continues with the fault lying to the northern fringe of Madagascar. (Mercator projection)

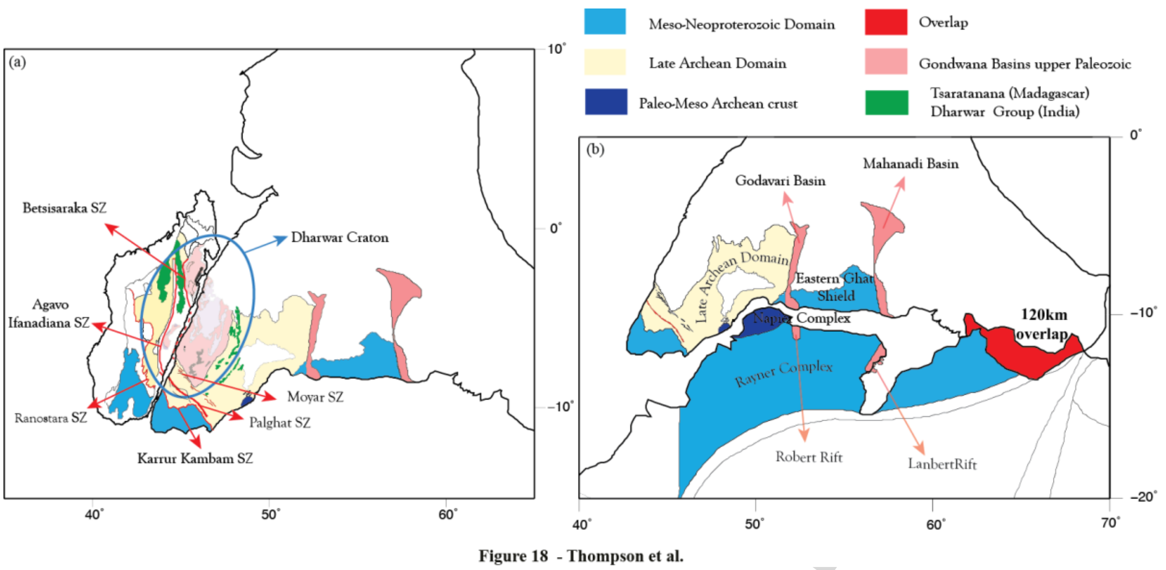

Figure 18: a) Map showing our reconstruction of India and Antarctica (with respect to Africa). The Archean rocks of the Napier complex in Antarctica and the Eastern Ghats shield share similarly geochemical characteristics. The Rayner Complex extends from Enderby Land (Antarctica) into the Mesoproterozoic rocks of the Eastern Ghats Granulite in India. Notice the alignment of the conjugate Carboniferous-Permo Cretaceous rift basins of Godavari and Mahanadi in India, and the Lambert and Robert rift valleys in Antarctic. The ~120km overlap between India and Antarctica (red area) within Southern Bangladesh is explained by the not clearly defined limits of the India plate within the region, and the characterization of the region by large compressional deformation. B) Map showing our reconstruction of India and Madagascar (with respect to Africa). Note the correspondance of Eastern Dharwar craton of India and the Antongil-Masora cratons of Madagascar. The Precambrian shear zones of Agavo Ifadiana of Madagascar fits the Palghat shear zones of India. This results in alignment of Archean and Mesoproterozoic rocks in both in Madagascar and India. (Mercator projection).

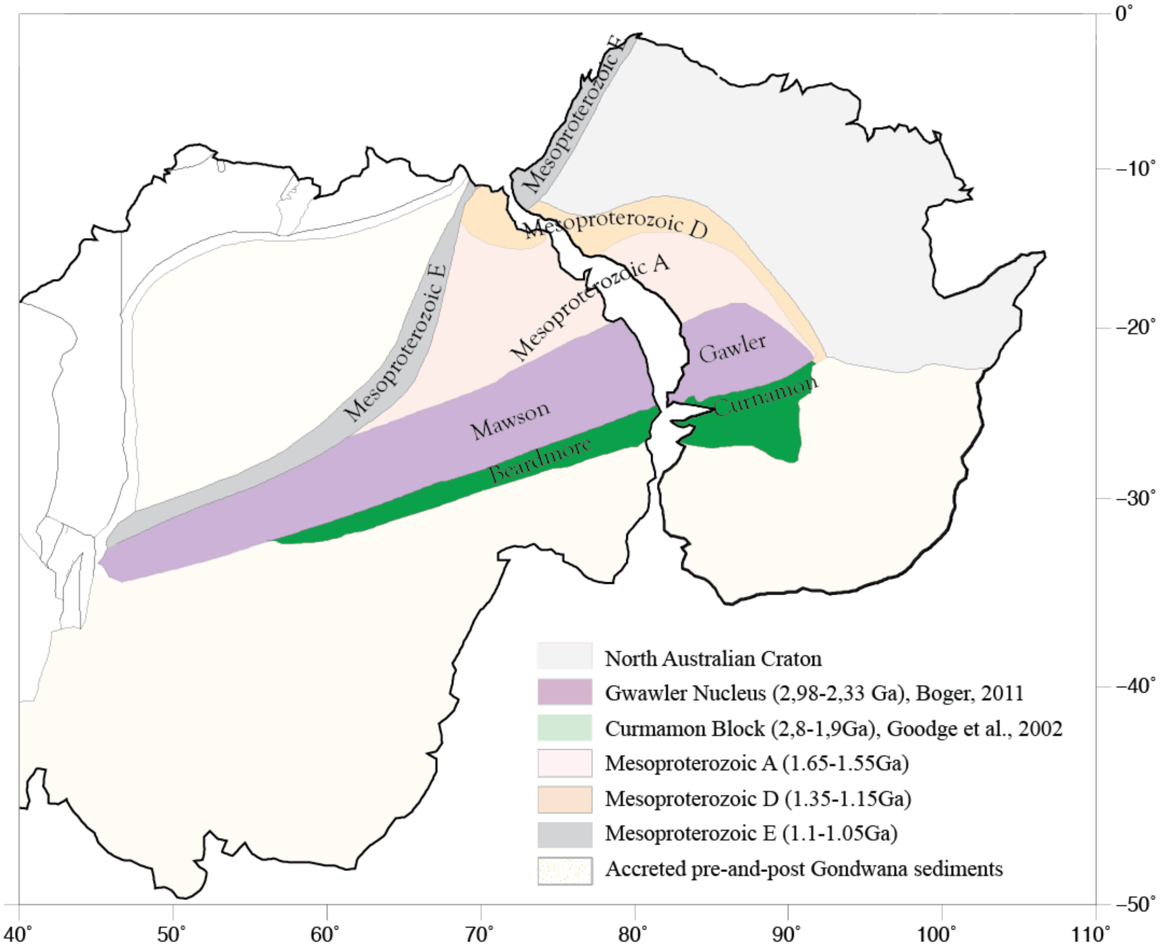

Figure 19 - Thompson et al.

Figure 18: Map showing our reconstruction of Australia and Antarctica (with respect to Africa). Notice the alignment of the Beardmore and Curnamona blocks, and the continuation of the Mesoproretozoic rocks (Boger, 2011) between Antarctica and Australia. (Mercator projection).

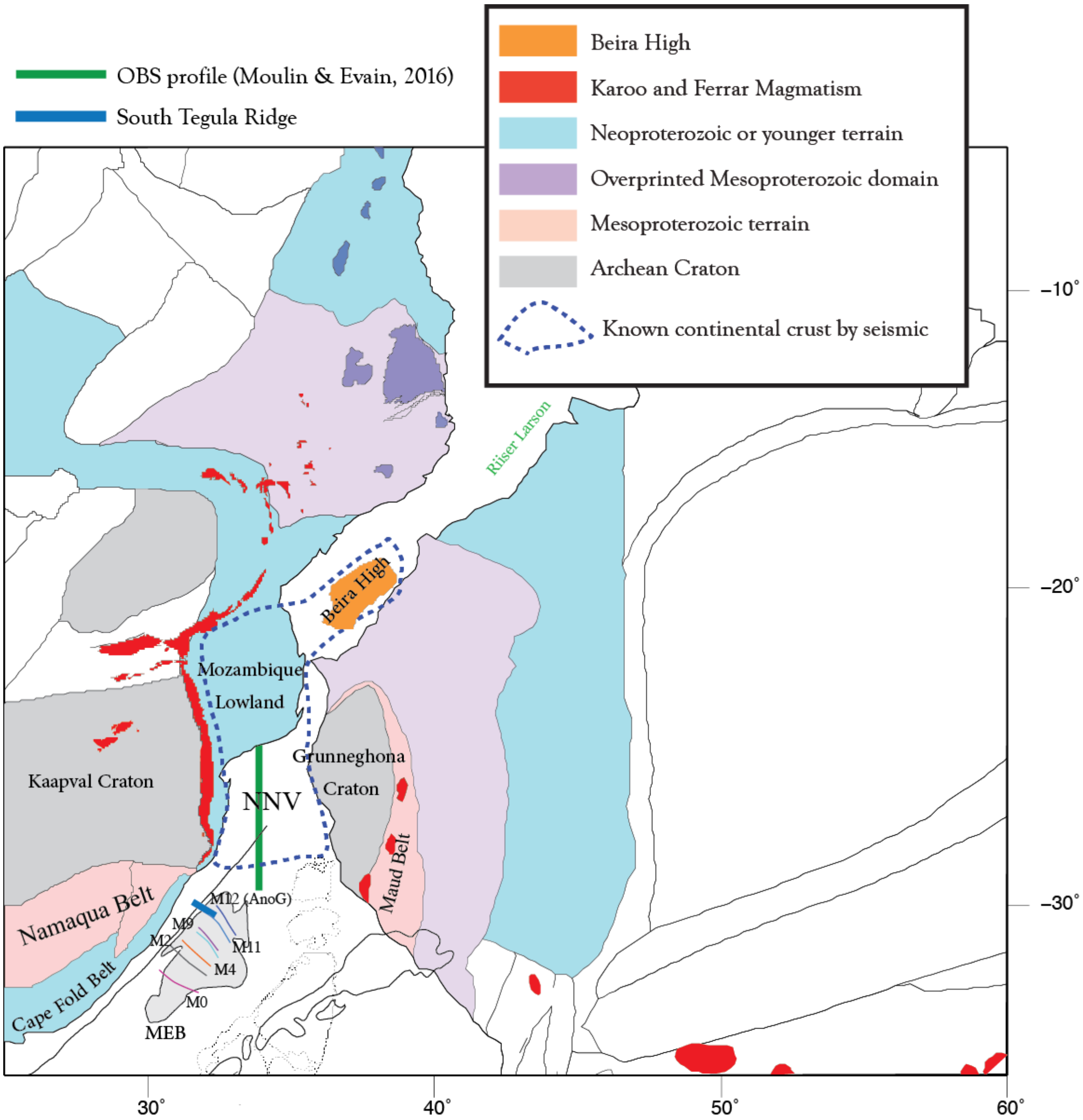

Figure 20 - Thompson et al.

Figure 20: Zoom of figure 16, showing perfect alignment of Precambrian shear zones of the Agavo Ifadiana shear zones of Madagascar to the Palghat shear zones of India respectively. It also shows the full extent of the Pan-African orogenic event and the Karoo volcanism in Gondwana. (Mercator projection)

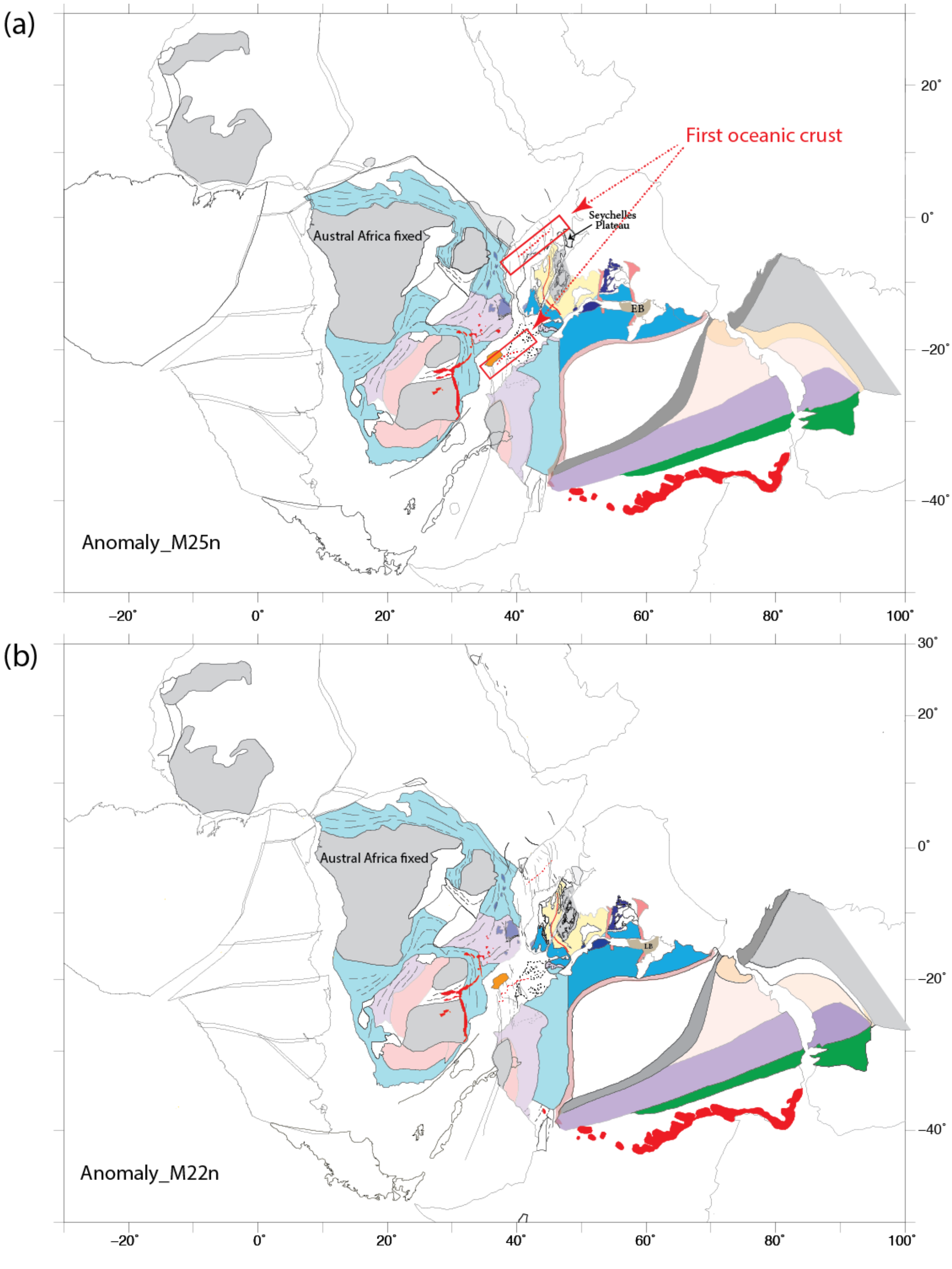

Figure 21 - Thompson et al.

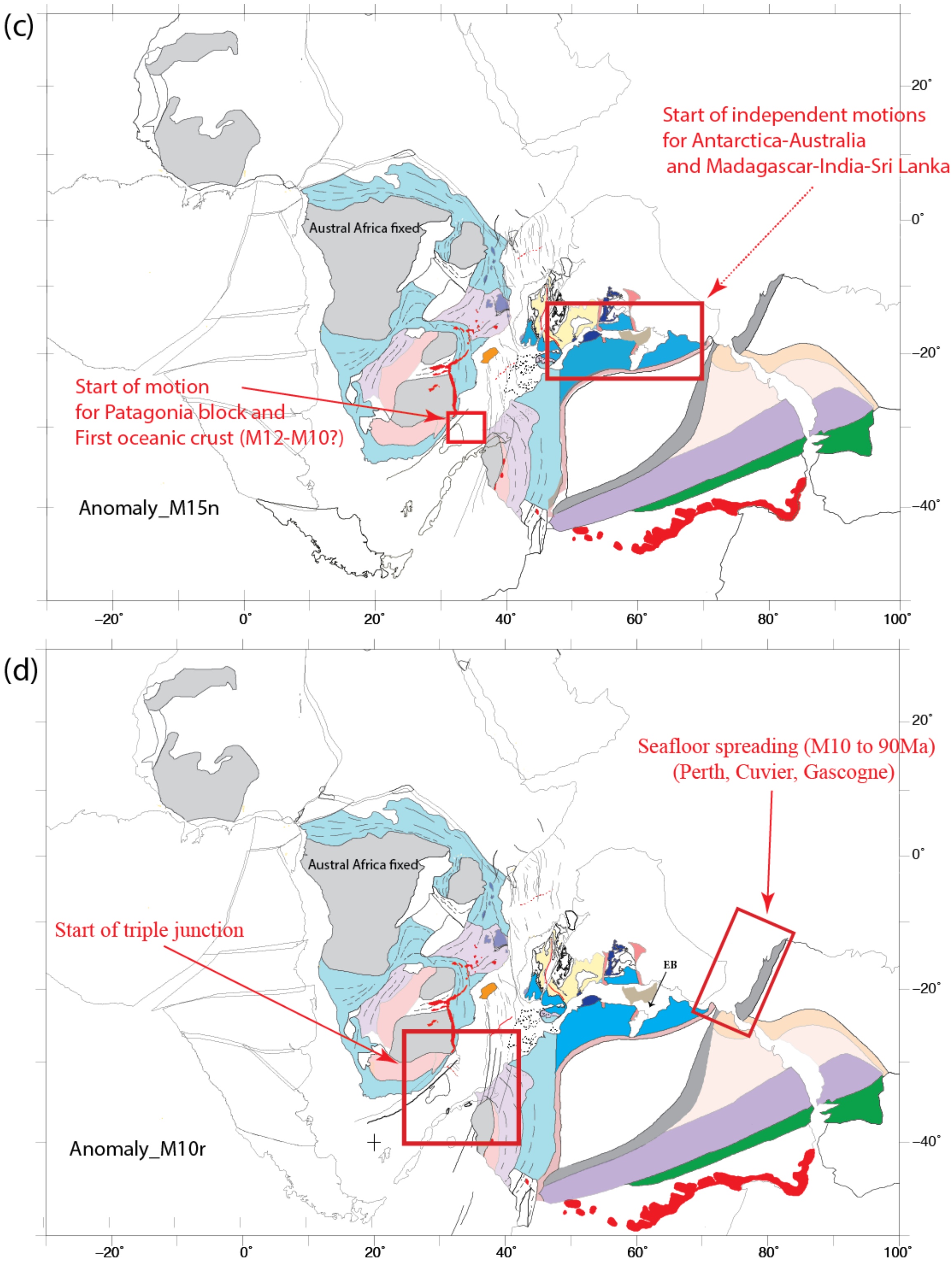

Figure 21 (continue) - Thompson et al.

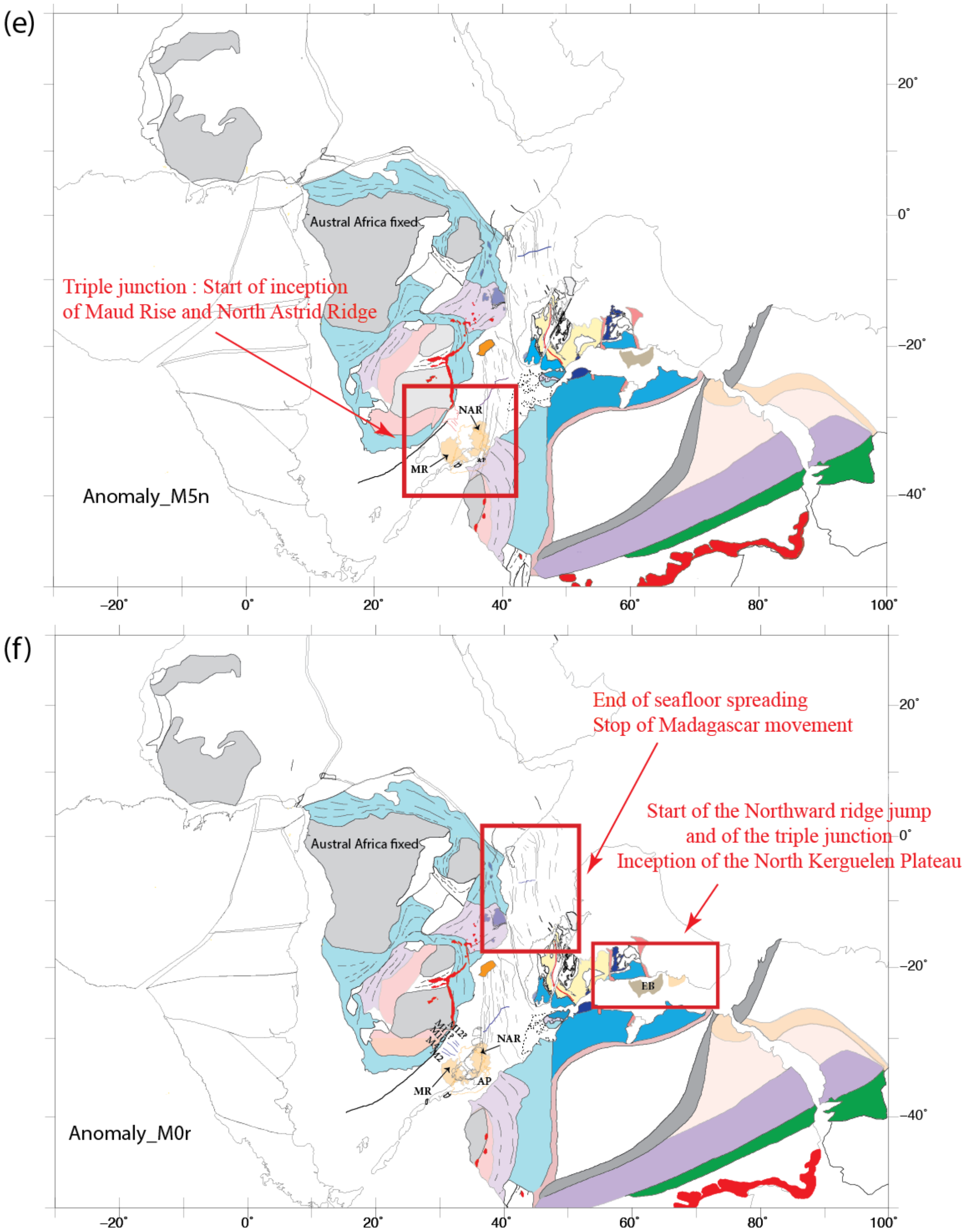

Figure 21 (continue) - Thompson et al.

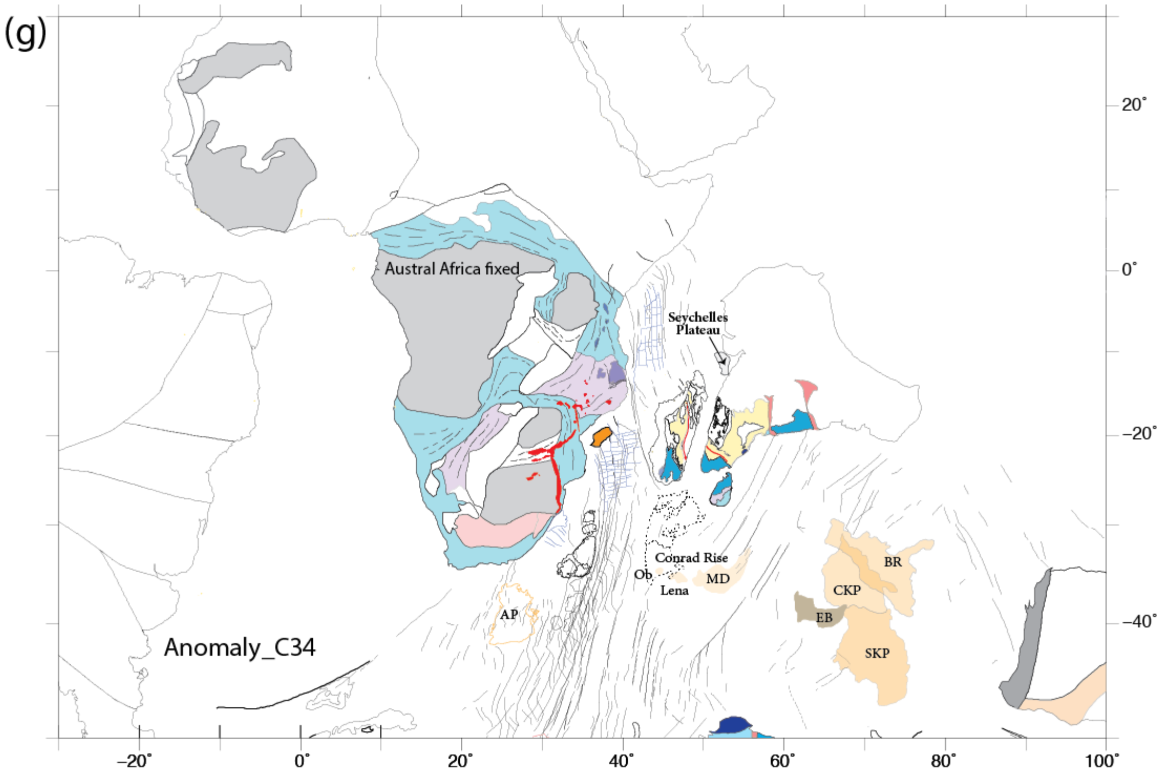

Figure 21 (continue) - Thompson et al.

Figure 21 : Reconstructions of the Indian Ocean at anomaly from the mid-late Jurassic (M25) to chron C34. (a) The break-up of Gondwana was accompanied by active seafloor spreading in the Western Somalia and Mozambique Basins with the formation of first oceanic crust at M25. (b) Reconstruction of the Indian Ocean at anomaly at M22 ; (c) Reconstruction of the Indian Ocean at anomaly at M15. (d) Reconstruction of the Indian Ocean at anomaly at M10r. This period saw large scale plate reorganisation in the Indian Ocean, leading to the formation of Curvier, Perth and Gascogne basins on the northwestern Australian margin (Veevers, 1988), breakup of the South Atlantic Ocean, and the formation of the first oceanic crust in the North Natal Valley. (e) Reconstruction of the Indian Ocean at anomaly at M5. (f) Reconstruction of the Indian Ocean at anomaly at M0r. The Madagascar-Greater India-Sri Lanka block stopped its southward drift from Africa at M0. The accretion in the Curvier, Perth and Gascogne basins also stopped at M0. The South Mozambique Ridge, Maud Rise, Agulhas Plateau, and northern part of the Astrid Ridge overlap at the Southern Mozambique Ridge at M0, which means they may hve emplaced during that time, possibly due to anormalous volcanism related to the Triple Junction between Africa, Antarctic and Falkland plates. The North Kerguelen Plateau may have been initiated around this time. (g) Reconstruction of the Indian Ocean at anomaly C34. Breakup and first oceanic recorded between Madagascar and India, and Australia and Antarctica. Anomalous oceanic plateaus (Conrad Rise, Crozet Ridge, Del Cano Rise and the South Madagascar Ridge) became emplaced during this period. The Del Cano Rise is a companion feature of the southern Madagascar according to Goslin, 1981. The Middle Kerguelen Plateau and the Broken Ridge were emplaced around this time. The Chagos- Laccadive , the Ninetyeast Ridges, North Kerguelen Plateau may have been emplaced during this period.

AP: Agulhas Plateau; BR: Broken Ridge; CKP: Central Kerguelen Plateau; EB: Elan Bank; MD Marion Dufresne seamounts; MR: Maud Ridge; NAR: North Astrid Ridge; SKP : South Kerguelen Plateau; SP: Seychelles Plateau. Mercator projection.

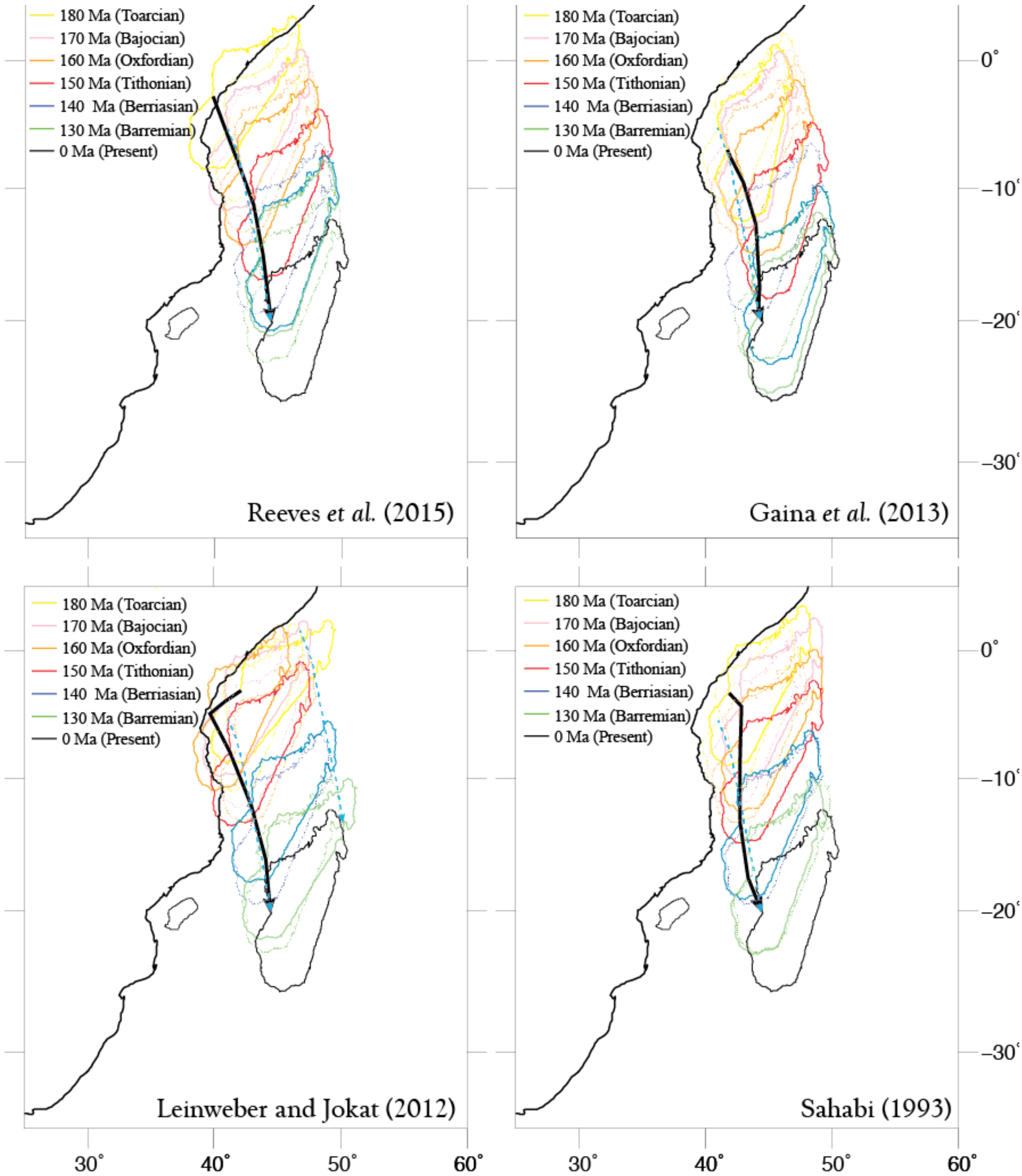

Figure 22: (a) Map showing the evolution of Madagascar in (Reeves *et al.*, 2015; Gaina *et al.*, 2013; Leinweber and Jokat, 2012; Sahabi, 1993), compared in with the evolution of Madagascar in our model. The black arrows indicate the direction of movement of the plates through time

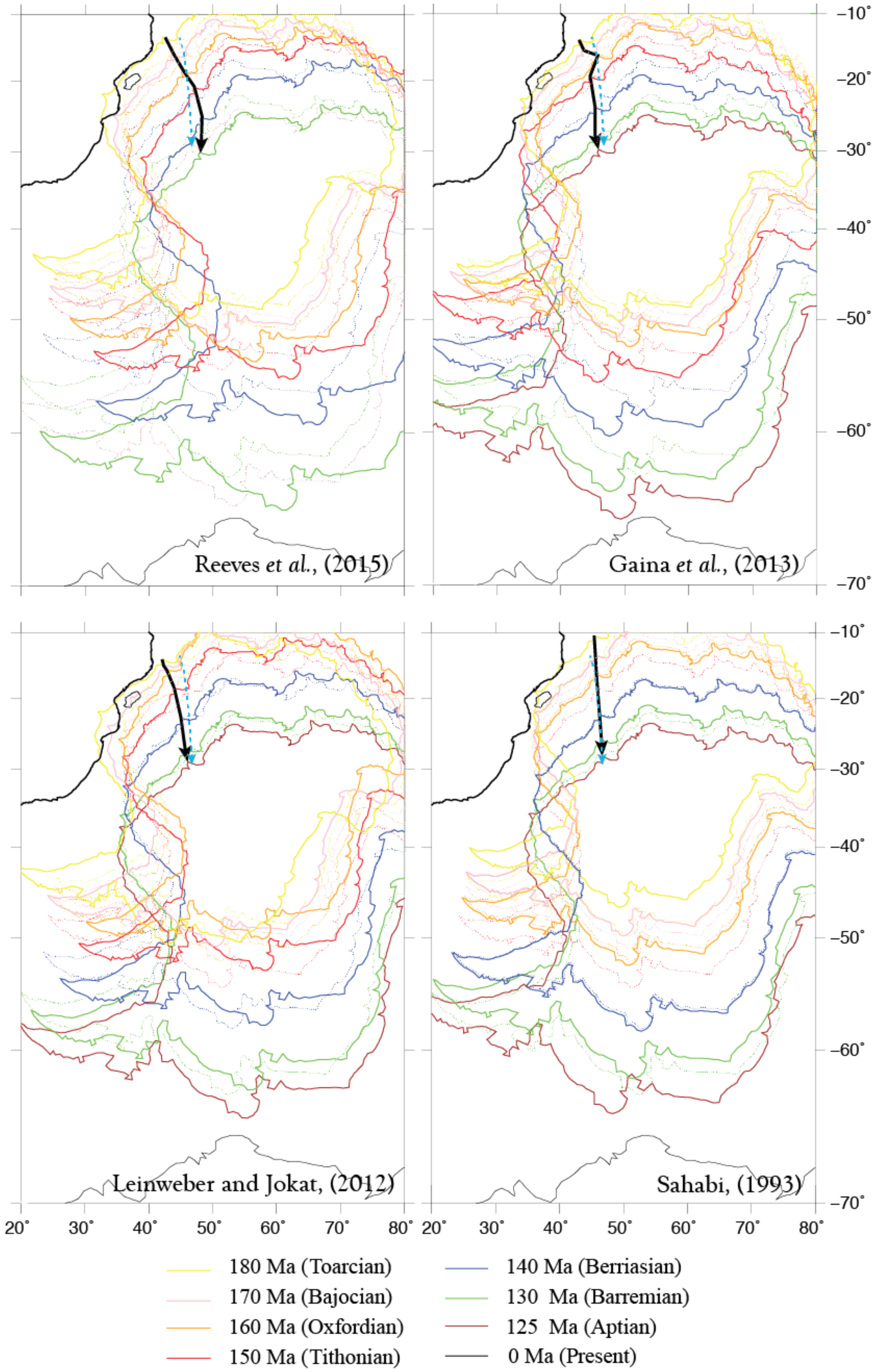

Figure 23: (a) Map showing the evolution of Antarctica in (Reeves *et al.*, 2015; Gaina *et al.*, 2013; Leinweber and Jokat, 2012; Sahabi, 1993), compared in (b) with the evolution of Antarctica in our model. The black arrows indicate the direction of movement of the plates through time. Mercator projection.