ANNÉE 2017

THÈSE / UNIVERSITÉ DE RENNES 1
sous le sceau de l'Université Bretagne Loire

pour le grade de

DOCTEUR DE L'UNIVERSITÉ DE RENNES 1
Mention : Sciences de la Terre

Ecole doctorale EGAAL

JOSEPH OFFEI THOMPSON

Préparée à l'unité de recherche UMR 6118 CNRS
Géosciences Rennes
UFR Sciences et Propriété de la Matière

The opening of the Indian Ocean: what is the impact on the East African, Madagascar and Antarctic margins, and what are the origins of the aseismic ridges?

Thèse soutenue à Brest
le 21 Novembre 2017

devant le jury composé de :

Professor Mohamed SAHABI
Professor Faculté des sciences d'El Jadida, Moroc/examinateur

Dr Stefane MAHAJANE
Geoscientist National Petroleum Institute Maputo/examinateur

Professor Maarten de WIT
Professor, Nelson Mandela University/ rapporteur

Dr Wilfred JOKAT
Researcher, Alfred Wegener Institute/ rapporteur

Dr Charlotte NIELSON
(Geological Engineer Total) – examinateur

Professor François GUILLOCHEAU
Professor Department of Geoscience,
Université de Rennes 1 / directeur de thèse

Dr Maryline MOULIN
(Researcher Ifremer) / co directeur de thèse

Dr Daniel ASLANIAN
(Researcher Ifremer) / co directeur de thèse

Philippe de Clarens
(Researcher Total) / co directeur de thèse

ANNÉE 2017

THÈSE / UNIVERSITÉ DE RENNES 1
sous le sceau de l'Université Bretagne Loire

pour le grade de

DOCTEUR DE L'UNIVERSITÉ DE RENNES 1
Mention : Sciences de la Terre

Ecole doctorale EGAAL

JOSEPH OFFEI THOMPSON

Préparée à l'unité de recherche UMR 6118 CNRS
Géosciences Rennes
UFR Sciences et Propriété de la Matière

The opening of the Indian Ocean: what is the impact on the East African, Madagascar and Antarctic margins, and what are the origins of the aseismic ridges?

Thèse soutenue à Brest
le 21 Novembre 2017

devant le jury composé de :

Professor Mohamed SAHABI
Professor Faculté des sciences d'El Jadida, Moroc/examinateur

Dr Stefane MAHAJANE
Geoscientist National Petroleum Institute Maputo/examinateur

Professor Maarten de WIT
Professor, Nelson Mandela University/ rapporteur

Dr Wilfred JOKAT
Researcher, Alfred Wegener Institute/ rapporteur

Dr Charlotte NIELSON
(Geological Engineer Total) – examinateur

Professor François GUILLOCHEAU
Professor Department of Geoscience,
Université de Rennes 1 / directeur de thèse

Dr Maryline MOULIN
(Researcher Ifremer) / co directeur de thèse

Dr Daniel ASLANIAN
(Researcher Ifremer) / co directeur de thèse

Philippe de Clarens
(Researcher Total) / co directeur de thèse

PAMELA
PAssive Margins Exploration LAboratories

Ifremer

Acknowledgement

My profound gratitude goes to Maryline Moulin (Researcher IFREMER), Daniel Aslanian (Researcher IFREMER), François Guillocheau (Professor University of Rennes 1) and Philippe de Clarens (TOTAL), my supervisors for the love, kindness, support, and knowledge they have impacted me during the period of this thesis. They made my stay in Brest and my work at IFREMER the best time of my life so far. They ensured I lack nothing, and that all the support, tools, softwares, and materials I needed for the research were available to achieve the objectives of the research. Their love, kindness, competence and life philosophies has influenced greatly my attitude to life. I will forever remember the times we shared together, in Ifremer, during the MOZ3-5 expedition, at Pau, and in Ghana. These are beautiful moments that will forever remain with me, and I am grateful to have shared with you. I got my greatest birthday gift so far from Maryline last year during my 30th birthday with a boat ride and fishing expedition together with João Marcelo Pinheiro and Pascal Pelleau. A moment I greatly cherish. The kindness and support of Daniel has been unimaginable throughout these years. His life has greatly influence me. On MOZ3-5 he will always come and give me a relieve so as not to miss out on the fun times; despite working all day. I appreciate the love you showed me Daniel. My first encounter with François is unforgettable, the warm embrace and the great laughs left an unforgettable impression on me. I remember I called him Professor François Guillocheau, and he said no no, just call me François and is okay. It is an unforgettable experience for me.
Philippe and I share lots of memorable moments together; times at the coffe, the seismic sessions, and the amusing moments bargaining the African hat in Ghana. All these are beautiful moments I cherished.

I am extremely indebted to Mikael Evain, Pascal Pelleau, Sylvain Bermell, Phillipe Schnurle, Mathilde Pitel, whose friendliness, competence and specialization in GMT, Placa, Arcgis, I greatly benefited. I say a big thank you to you all. I am very grateful for the kind assistance and the laughs we shared throughout my work at Ifremer.

I profoundly thank Jean-François Bourillet (Chief of Pamela Project IFREMER) and Philippe Bourges (Formal Chief of the Pamela project TOTAL), Jean-Noel Ferry (Formal Chief of the Pamela project TOTAL) and Jacques Durand (Current Chief of the Pamela project TOTAL), Nabil Sultan (Head Department of Marine Geoscience), for their kind support, and prompt assistance in making the fund available for the research, the trips, seminars and conferences.

I particular want to say thank you to all my colleagues on the Pamela project, and friends at the office who have directly and indirectly contributed to the success of this research. To Angelique Lepretre, Fanny Verrier, Simon Courgeon, Guillaume Michel, Jean-Pierre Ponte,
Antoine Delaunay, Guillaume Baby, Evangelia Batsi, Romain Pellen, and Massinissa Benabdellouahed, I say thank you.

I am extremely grateful to Prof Mohamed Sahabi (Faculté des sciences d'El Jadida), Dr Wilfred Jokat (Researcher Alfred Wegener Institute), Professor Maarten de Wit (Professor AEON-ESSRI, Mandela University, South Africa), Dr Stefane Mahajane (Geoscientist National Petroleum Institute of Maputo) for accepting to be Jury for the PhD defence. They are recognized internationally for their great contribution to geology, and their immense research in their various fields. My first encounter with these great men left unforgettable and intensely life changing experience.

I thank all participants of the two months long Pamela MOZ3-5 expedition in the Mozambique Channel; especially Sylvie Leroy, P. Afonso, Raymi Castilla, Maximillian Fischer, and Catarina Rhombe, and all the researchers, technicians and secretaries of the Department of Marine Geosciences of IFREMER and Geoscience Department University of Rennes 1 for their counsel, kindness, and all the interest showed in this research work.

Remerciements

Ma profonde gratitude va à Maryline Moulin (chercheur IFREMER), Daniel Aslanian (chercheur IFREMER), François Guillocheau (Professeur Université de Rennes 1) et Philippe de Clarens (TOTAL) mes superviseurs pour leur gentillesse et leur soutien tout au long de ma thèse. Ils ont rendu mon séjour à Brest et à IFREMER un des meilleurs moments de ma vie. Ils se sont assuré que tout allait pour le mieux pour moi, et que tout le support matériel - les outils, les logiciels… - dont j'avais besoin étaient à ma disposition pour atteindre les objectifs de recherche. Leur affection, leur gentillesse, leurs compétences et leurs philosophies ont beaucoup influencé mon attitude envers la vie. Je me souviendrai pour toujours les moments que nous avons partagés ensemble, à Ifremer, et lors de l'expédition MOZ3-5, à Pau et au Ghana. Ce sont de beaux moments qui resteront pour toujours, et dont je suis reconnaissant de partager avec vous. J'ai eu ma plus grande fête d'anniversaire par Maryline l'année dernière lors de mon 30e anniversaire avec une promenade en bateau avec João Marcelo Pinheiro et Pascal Pelleau. Un moment que je chéris grandement. La gentillesse et le soutien de Daniel ont été inimaginables tout au long de ces années. Sa vie m'a grandement influencé. Sur MOZ3-5, il venait toujours s'assurer que tout allait bien pour moi, pour me soulager mais aussi partager des moments amusants, malgré le fait de travailler toute la journée et d'être fatigué. J'apprécie l'amour que tu as montré Daniel.

Ma première rencontre avec François est inoubliable, l'acceuil chaleureux et les grands rires m'ont laissés une impression inoubliable. Je me souviens que je l'ai appelé professeur François Guillocheau, et il a dit non non, appelle-moi simplement François. C'est une expérience inoubliable pour moi. Philippe et moi-même partageons beaucoup de moments mémorables; boire le café, pendant le travail sismique, et les moments amusants quand on a négocié le chapeau africain au Ghana. Tous ces moments sont magnifiques et je les ai appréciés.

Je suis extrêmement redevable à Mikael Evain, Pascal Pelleau, Sylvain Bermell, Philippe Schnurle, Mathilde Pitel, dont la gentillesse, la compétence et la spécialisation dans GMT, Placa, Arcgis, m'ont grandement aidé. Je vous remercie beaucoup. Je suis très reconnaissant pour l'aide aimable et les rires tout au long de mon travail à l'Ifremer.

Je remercie profondément Jean-François Bourillet (Chef de Pamela Project IFREMER) et Philippe Bourges (Chef formel du projet Pamela TOTAL), Jean-Noel Ferry (Chef formel du projet Pamela TOTAL) et Jacques Durand (Chef actuel de la Projet Pamela TOTAL), Nabil Sultan (chef de Géosciences Marines), pour leur soutien aimable, assistance rapide et mise à disposition du financement de cette recherche, des voyages, des séminaires et des conférences.

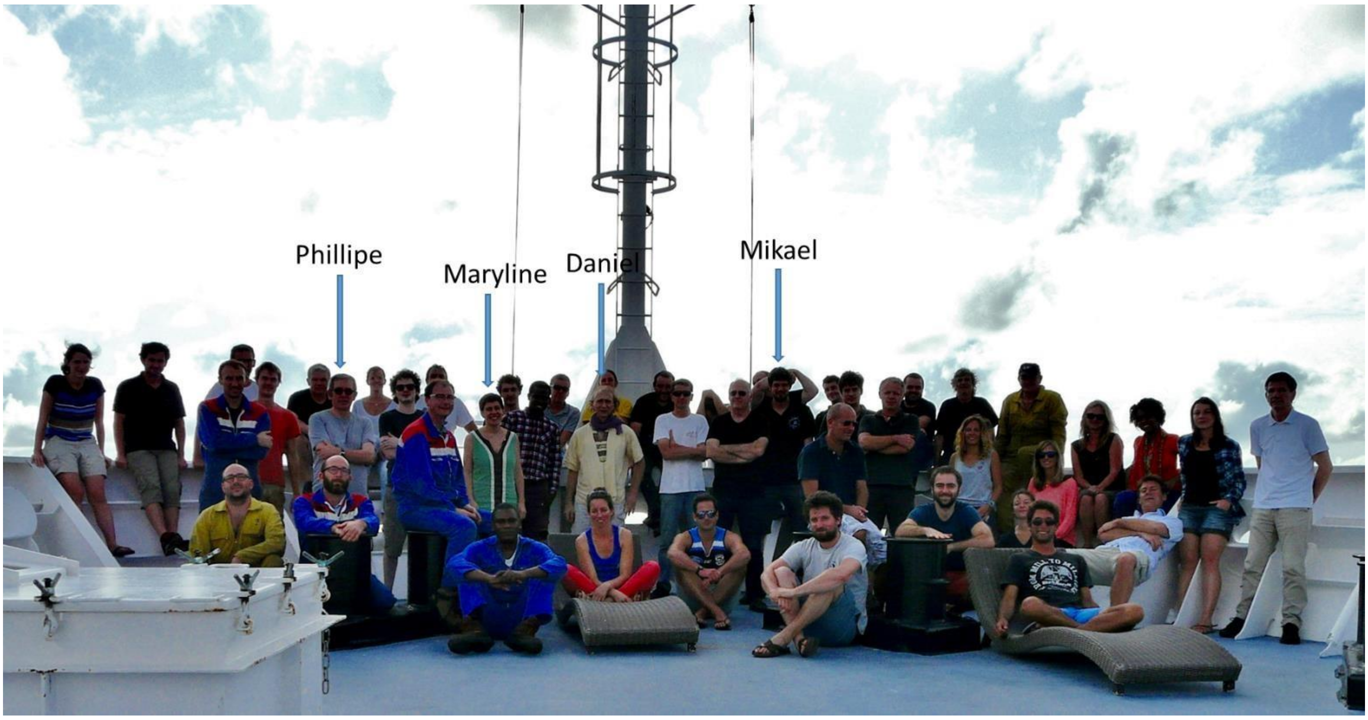
Je tiens particulièrement à remercier tous mes collègues du projet Pamela et des amis au bureau qui ont directement et indirectement contribué au succès de cette recherche. Pour Angélique Leprêtre, Fanny Verrier, Simon Courgeon, Guillaume Michel, Jean-Pierre Ponte, Antoine Delaunay, Guillaume Baby, Evangelia Batsi, Romain Pellen et Massinissa Benabdellouan, je vous remercie.

Je remercie également Dr Wilfred Jokat (Institut Chercheur Alfred Wegener), Professeur Martin de Wit (Professeur Département des sciences géologiques, Université du Cap, Rondebosch 7700, Afrique du Sud), Dr. Stefane Mahajane (Institut géoscientifique national de pétrole de Maputo) pour accepter d'être le jury pour la soutenance de ma thèse. Ils sont reconnus internationalement pour la grande contribution à la géologie et leur immense recherche dans leurs différents domaines. Ma première rencontre avec ces grands hommes a laissé une expérience inoubliable.

Je remercie tous les participants de l'expédition de deux mois Pamela MOZ3-5 dans le canal du Mozambique; en particulier Sylvie Leroy, P. Afonso, Raymi Castilla, Maximillian Fischer et Catarina Rhombe, ainsi que tous les chercheurs, techniciens et secrétaires du département Géosciences Marines de l'IFREMER et du département Géosciences de l'Université de Rennes 1 pour leurs conseils, leur gentillesse et l'intérêt dont ils ont fait preuve pour ce travail de recherche.


Adventure


Maryline
Daniel
Joseph
Stefane


Phillipe
Maryline
Daniel
Mikael

Abstract:

Gondwana, formed during the Pan-African Orogeny between 720 and 550Ma, composed of Archean and Paleoproterozoic Cratonic cores surrounded by accreted progressively younger terrains of Mesoproterozoic and Neoproterozoic age. The event saw the closure of a number of large ocean basins and the collision of several cratonic blocks to form the largest unit of continental crust (Pangea) on earth for more than 200Ma from the Late Neoproterozoic 550 Ma to the Carboniferous at about 320 Ma. 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 super-continent remains enigma. Current reconstruction models of the Indian Ocean are characterized by large gaps, overlaps and misfits of major structural and cratonic bodies in full-fit reconstruction, and positions of tectonic blocks that are inconsistent with field observations, a phenomenon sustained by inadequate data, long standing debates and lack of consensus on the nature of major structures and basins in the ocean domain. Past attempts to reconstruct 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. Examination of these models and their consequences on the continental passive margins brings to light critical scientific questions they pose, and the incoherencies that exist between them in their initial fit. This work presents a comprehensive study of the structure of the Precambrian basement, Paleozoic marginal and rift basins of all the plates surrounding the Indian Ocean, examine the architecture and geochronological composition of their composing cratons and crustal blocks, and delineating important structural markers in order to accurately juxtapose them in the initial fit. We introduce a new holistic model of Gondwana's evolution achieved through a combination of onshore and offshore geological and geophysical data published integrated with newly acquired during the Pamela MOZ3-5 campaign. Our new model is coherent with current data interpretations in the Indian Ocean, and is consistent with all existing knowledge about major structures constituting Gondwana. The model permits full extent of major cratonic, volcanic and sedimentary structures within the super-continent, and presents the best candidate at present day upon which further work could be carried.

Résumé :

Le Gondwana a été formé pendant l'orogenèse panafricaine, de 720 à 550Ma, il est composé de noyaux cratoniques Archéen et Paleoprotérozoïque, auxquels ce sont accrétés des terrains progressivement plus jeunes, d'âge Mésoprotérozoïque et Néoprotérozoïque. L'événement a vu la fermeture d'un certain nombre de grands bassins océaniques et la collision de plusieurs blocs cratoniques pour former la plus grande unité de croûte continentale sur Terre et ce, sur plus de 200Ma, depuis le Neoprotérozoïque tardif 550 Ma jusqu'au Carbonifère à environ 320 Ma. Sa fragmentation ultérieure a fait l'objet de plusieurs études au cours des cinq dernières décennies, mais la question très importante de la véritable géométrie initiale du super-continent reste une énigme. Les modèles de reconstruction actuels ne permettent d'expliquer un certain nombre de lacunes, de chevauchements et d'incohérences entre les limites des grands domaines structuraux et cratoniques, et les données de terrain. Cette situation résulte de l'utilisation d'une base de données incomplète, de la persistence d'anciens débats et de l'absence de consensus sur la nature des différentes structures et bassins du domaine océanique. Les tentatives passées de reconstruction de l'océan ont conduit à des modèles variés et complexes, avec leur propre logique et différentes limites géographiques, dont la validité et les hypothèses sous-jacentes nécessitent des tests à la lumière des données géologiques et géophysiques mondiales actuelles. Notre examen de ces modèles et de leurs conséquences sur les marges passives continentales met en lumière les questions scientifiques très critiques qu'ils posent et les incohérences qui existent entre eux dans la reconstruction intégrale. Cette thèse présente une étude complète de la structure du sous-sol Précambrien, des bassins Paléozoïques marginaux et des rifts de toutes les plaques constituant l'océan Indien, en examinant l'architecture, la composition géochronologique de leurs blocs cratoniques et crustaux mais aussi en délimitant d'importants marqueurs structuraux afin de les juxtaposer avec précisions dans des reconstructions intégrales. Nous présentons un nouveau modèle holistique de l'évolution de Gondwana réalisé grâce à une combinaison de données géologiques et géophysiques terrestres et offshore publiées et nouvellement acquises lors de la campagne Pamela MOZ3-5. Notre nouveau modèle est cohérent avec les interprétations actuelles des données dans l'océan Indien, et, est conforme à toutes les connaissances que nous avons sur les grandes structures constituant le Gondwana. Le

modèle permet de couvrir l'étendue complète des principales structures cratoniques, volcaniques et sédimentaires dans le super-continent et représente, à l'heure actuelle, le meilleur candidat sur lequel d'autres travaux pourraient être réalisés.

Table of Contents

List of Figures

Figure Page

Appendix Figures

List of Tables

Figure Page

JURY

Dr Wilfred Jokat (Researcher Alfred Wegener Institute) – Reporter

Professor Maarten de Wit (Professor Nelson Mandela University, South Africa) – Reporter
Prof Mohamed Sahabi (Faculté des sciences d'El Jadida) – Examiner

Dr Stefane Mahajane (Geoscientist National Petroleum Institute of Maputo) – Examiner

Dr Maryline Moulin (Researcher Ifremer) – co director of thesis

Dr Daniel Aslanian (Researcher Ifremer) – co director of thesis

Prof François Guillocheau (Professor Department of Geoscience, Université de Rennes 1) – director of thesis.

Philippe de Clarens (Researcher Total) – co director of thesis.

Dr Charlotte Nielson (Geological Engineer Total) – co director of thesis.

CHAPTER 1: INTRODUCTION

Chapter 1

The Indian Ocean is the most complicated and least understood of the world's major oceans. Its evolution is of considerable geological importance, as the destruction of the ocean of Tethys was accompanied by the formation of the Indian Ocean southward (Kazmin, 1989; Gnos et al., 1997). The early breakup history of Gondwana is preserved in the Indian Ocean along the East Africa, Madagascar, and Antarctica passive margins (McKenzie and Sclatter, 1971; Smith and Hallem, 1970; Tarling et al. 1972; Sahabi, 1993; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber andJokat, 2012; Seton et al., 2012; Torsvik et al., 2012, 2008; Gaina et al., 2007, 2013, 2015; Reeves et al., 2002, 2015). These margins recorded the oldest sediments and magnetic anomalies of the Indian Ocean, and therefore crucial to our understanding of the initial configuration of Gondwana and its early breakup history during the Jurassic time. However, the reconstruction modelling of the Indian Ocean presents lots of challenges to Geodynamic modelers, linked to the numerous and diverse reconstruction models of the ocean, due largely to unanswered critical scientific questions that remain standing regarding the formation and evolution of the ocean.

This chapter introduces the history of plate tectonic studies in the Indian and the different approaches used in the reconstruction model. We examine a number of reconstruction models of the Indian Ocean looking at their consequences on the passives margins and their underlying reasons. The chapter therefore throws more light on the complications reconstruction modeling in the Indian Ocean and their geodynamic implications.

1.1 INTRODUCTION

The disintegration of East Gondwana in the Mesozoic created the third largest of the world's oceans (The Indian Ocean), covering approximately 20% of the earth surface with an average depth of 3700m and a maximum depth of 8000m in the Diamantina Trench southwest of Perth,Western Australia. The ocean is bounded to the north by the Eurasian and the Indian plates, on its west by the African plate, east by the Australian plate, and south by the Antarctic plate (Figure 1).

The breakup history of Gondwana is complex. The disintegration of the supercontinent along the Mesozoic margins of East Africa, Antarctic, Madagascar was preceded by several episodes of tectonism and magmatism whose interpretation and association with breakup remains enigmatic. Figure 2 shows the segmentation and complexity of the East African margin. The margin is segmented into three domains, depicted by the arrows. The segments correspond to the movement of the Madagascar, Antarctic and the Patagonia-Falkland plates, respectively from the African tectonic plate. Although East Gondwana may have moved as a cohesive unit during the early drift history, these plates subsequently moved free from each other with independent seafloor spreading record history. Fortunately, an important characteristics of the Indian Ocean is the absence of large number of active trenches (Mckenzie and Sclatter, 1971), hence, providing that the old seafloor produced in the course of the ocean's evolution have not been subducted, and that their interpretation should not pose much difficulties towards understanding the initial geometry of Gondwana (McKenzie and Morgan 1969). The early breakup history of the Indian Ocean is preserved along the passive margins of East Africa, Madagascar, and Antarctica (McKenzie and Sclatter, 1971; Smith and Hallem, 1970; Tarling et al. 1972; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber et al., 2012; Seton et al., 2012; Torsvik et al., 2012, 2008; Gaina et al., 2015, 2013, 2007; Reeves et al., 2002, 2015; Davies et al., 2016). These margins record the oldest sediments and magnetic anomalies of the Indian Ocean, and are therefore crucial to our understanding of Gondwana's initial configuration and the early drift history.

Although Cenozoic kinematic history of the Indian Ocean is well constrained due to the clear spreading lineaments (fracture zones) and magnetic anomalies (Royer *et al.*, 1988; Sahabi, 1993; Bernard *et al.*, 2005; Gaina *et al.*, 2007; Eagles and Hoang, 2013; Gibbons *et al.*, 2013), little is known about the immediate pre-breakup history and the true configuration of

Gondwana due to lack of quality geological and geophysical data, and difficulties in interpreting magnetic anomalies along the cotitnental margins, (Gaina *et al.*, 2007; Leinweber and Jokat, 2012; Leinweber *et al.*, 2013), due to long standing debates and lack of consensus on the nature of major structures and basins in the ocean. Past attempts to reconstruct the ocean has led to varied and complex models (Figure 3) whose validity and underlying assumptions require testing in the light of increasing geological and geophysical data.

There is currently no consensus on a number of key scientific questions in the ocean (See chapter 2, page 21), resulting in problematic and incoherent model proposals. And although we currently have some ideas about the direction of movements of the plates, mainly based on gravity, magnetic, and some onshore and offshore data; detailed kinematic reconstructions of Gondwana's initial geometry is problematic (Powells *et al.*, 1980; Seton *et al.*, 2012; Davies *et al.*, 2016), with large gaps and overlaps in reconstructions, and motions of tectonic blocks and plates that are inconsistent and incoherent with field observation and independently modeled motions of neighboring tectonic plates (Figure 3). Indeed, many researchers working with the drift hypothesis disagree on the respective positions of the tectonic plates making up Gondwana (Africa, India, Australia, Sri Lanka, and Antarctica) (Smith and Hallem, 1970; McKenzie and Sclatter, 1971; Tarling *et al.*, 1972). It is also important to emphasize that wide differing opinions exist on the assumed paths by which these fragments of Gondwana have reached their present locations (e.g Smith and Hallem, 1970; Tarling *et al.* 1972; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber *et al.*, 2012; Seton *et al.*, 2012; Torsvik *et al.*, 2012, 2008; Gaina *et al.*, 2015, 2013, 2007; Reeves *et al.*, 2002, 2015).

Comprehensive examination of published reconsruction models and their consequences on the continental passive margins was undertaken in this study. The exercise brought to light very critical scientific questions that the models pose, and the incoherencies and varied differences that exist between them in the initial fit (McKenzie and Sclatter, 1971; Smith and Hallem, 1970; Tarling *et al.* 1972; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber *et al.*, 2012; Seton *et al.*, 2012; Torsvik *et al.*, 2012, 2008; Gaina *et al.*, 2015, 2013, 2007; Reeves *et al.*, 2002, 2015; Davies *et al.*, 2016).).

Modelers are divided on the true nature of the crust underlying some part of the continent (as the Limpopo Basin) and the aseismic ridges (the Mozambique Ridge, and the Madagascar Ridge), and the first oceanic crust along the East African margin. A number of these models

(e.g. Reeves and de Wit, 2000; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber *et al.*, 2012; Seton *et al.*, 2012; Torsvik *et al.*, 2012; Gaina *et al.*, 2015) assumed all intervening crust between Antarctica and Africa as oceanic. Putting the age of breakup close to the Karoo volcanic event, (183Ma, the time of formation of Lebombo Rooi Rand dykes), in their bid to simplify the reconstruction and to focus attention on resolving how tightly the Antartic plate can be fitted to Africa (eg. Jokat *et al.*, 2003). This assumption results in sharp narrowing of the continent–ocean transition between the plates, which has serious implications on the temporal and spatial evolution of the margin. The consequence is a possible 300km overlap or gap in the Limpopo Basin between the two plates depending on the nature (oceanic or continental) adopted for reconstruction. But this hypothesis has strong consequences on the rest of the jigsaw and does not fit newly acquired data as we will show.

Hence, to achieve a holistic constrain of the initial fit of Gondwana and to find some answers to the questions and debates, we adopted a multifaceted approach, by in-depth study and combination of onshore and offshore geological and geophysical in the Indian Ocean. Extensive study of the structure of the Precambrian basement, Paleozoic marginal and rift basins of all the plates constituting the Indian Ocean; examining the architecture and geochronological composition of their composing cratons and crustal blocks, and delineating structural markers in order to accurately juxtapose them.

The offshore studies involves interpretation of seismic reflection from TOTAL data base, and well data in the Mozambique Channel. In the Zambezi Basin, we produce structural map of the basin, delineating oceanic, continental, and transitional domains. In the Limpopo Basin, the lines were extended onshore to understand the distribution and trend of the previously described Landward Dipping Reflectors (Hinz 1981; Cox, 1992).

In addition, new seismic refraction and reflection data were acquired in the Mozambique Channel during the Pamela 3-5 campaign. The analysis of this survey is not presented in this work. However, Moulin *et al.* (in prep) presents preliminary results of this work. We use the result to further help us to constrain the initial fit. We further carryout a study of new published seismic and geochemical data on some of the long debated aseismic ridges and incorporate the results into our work.

Our new model of the Gondwana fit around 200Ma, and evolution of the Indian was therefore achieved through careful integration of on-land and offshore geological and geophysical data to produce what we believe is a more coherent model.

1.2 PROJECT AIMS AND OBJECTIVES.

The main objectives of this research work are:

(a) Compare the different published kinematic models at the same scale, the same geographical limits and with the same geological landmarks to examine their differences and incoherencies.

(b) Examine the nature of the Mozambique and Madagascar aseismic ridges and their role in the Indian Ocean evolution, and consequence on published models.

(c) Produce a new holistic model of Gondwana, on the basis of synthesis of:

i) Geophysical and geological data.

ii) On-land and offshore published and newly acquired data in the scope of the PAMELA project.

The Passive Margin Exploration Laboratories (PAMELA) project is an integrated research program on passive margins across the world with large research interest in topics such as geological structure, distribution of sedimentary bodies, margin instabilities, fluid transport, and ecosystems of the margins and in the ocean.

The project is a collaborative effort between Ifremer, Total Petroleum and top French Universities including Université de Rennes Geoscience, Institut Universitaire Européen de la Mer (IUEM), and Université Pierre et Marrie Currie-Paris (UPMC). It was formulated in December 2012 with the strong scientific aims of undertaking research to understand the paleogeography and evolution of the Indian Ocean through time, to understand the original positioning of the Gondwana plates in their pre-breakup history, examine the thermal evolution of the East African and Madagascan passive margins, the spatial and temporal distribution and deposition of the sedimentary systems during different climatic cycles, the distinction of carbonate system, recording of sea level changes, and the biodiversity of carbonate platforms underwater.

(d) Examine the consequence of the Gondwana's breakup on the East Africa, Antarctic and Madagascar passive margins.

1.3 INDIAN OCEAN PLATE RECONSTRUCTION STUDIES HISTORY.

Man for a longtime has harbored the idea that the current continental may have once formed a single supermass. Such suggestions were grounded on some observations stemming from the identification of same fossilized plant and animals on different continents [Example, fossil leafs of the seed fern Glossopteris was found in the 19th century, in India, Africa and South America (de Wit et al., 2001; de Wit, 2003, Leinweber, 2012 PhD thesis)].

Indeed, before the acceptance of the continental drift hypothesis of Wegener (1929) who proposed that all the continents were once formed a single supercontinent, which he called Pangaea, ideas of continental morphological fit were already been discussed in 1500's (Figure 4).

In 1596, Ortelius had adduced earthquakes and floods as the reason for America having been torn away from Europe and Africa.

Emile Argand, (1911), presented structural maps of Eurasia and the sedimentary basins which bordered its coastline during the Mesozoic and Tertiary, and considered Lemuria (part of the Indian Continent) to have experienced underplated during the formation of the Indian Ocean

Eduard Suess (1924), used the Glossopteris flora to add South America to the other land masses (Africa, Madagascar, India, Australia) he had already amalgamated into his recently christened supercontinent of Gondwanaland.

The theory that was widely accepted then was the Land-bridge hypothesis by de Acosta (1590) and the contraction hypothesis by the renowned French scientist de Beaumont (1552).

The land-bridge theory was an attempt to explain the known paleontological observation that a number of fossilized plants and animals of the same species and period can be found across the continents. This hypothesis was widely accepted although such bridging lands were not observed.

The contraction theory was also widely discussed during this time. The theory suggested that the planet was once a molten ball and in the process of cooling the surface cracked and folded up, creating the current mountains and plates we observe. The problem with this idea was that all mountain ranges should be approximately of the same age. However, such a phenomenon could not be proven, and therefore the theory could be not accepted.

The first map showing South America and Africa lying close together was published in 1858 by Antonio Snider-Pellegrini. Following that idea, Wegener published in 1915 a new theory (*Die Entstehung der Kontinente und Ozeane* – German version 1915; French version 1919).

Wegener's hypothesis contradicted the contraction theory, explaining that the continents do move, and in doing so their leading edges encounter resistance and thus compress and foldup into mountains. He supposed that the mechanisms causing the drift might be the centrifugal force of the Earth's rotation ("Polflucht") or the astronomical precession.

His inability to provide adequate explanation and geophysical mechanism for the forces responsible for the drifting of the continent and the strong prevailing belief that the earth was rigid and immovable, resulted in a dismissal of his ideas by most of the geological community at that time, and a twenty year delay in the acceptance of the Continental Drift Theory.

Holmes (1944), Harry Hess (1962) and Deitz (1961) later elaborated on one of his ideas that the mantle undergoes thermal convection to propose the Seafloor Spreading Hypothesis; suggesting that, the thermal convection is like a conveyor belt carrying continental fragments in opposite direction. Their work provided the mathematical and geological basis for the mechanism and forces responsible for the drifting of the plates leading to the acceptance by some scientists Wegener's Continental Drift Theory. Additionally, the 1960s saw several several developments in geology (e.g. start of plate tectonics), notably the discoveries of seafloor spreading and Wadati–Benioff zones.

Bullard et al., 1965, were the first to quantify the fit of continents (South America and Africa.

In the Indian Ocean, the original constraints for the continental drift hypothesis and the reconstruction of the plates was based on the shape of the continents (Wegener, 1929, and du Toit, 1937). Later constraints came from matching of geological facies, simultaneous marine transgressions on continental margins, and paleo-climatic indications (Smith and Hallem, 1970; Tarling *et al.* 1972; Dingle and Scrutton, 1974). There were wide differing opinions as to the respective positions of the plates and the initial configuration of Gondwana, ensuing an early debate between two initial models; the model of Wegener (1929) and that of du Toit (1937) for over three decades from 1937 to 1976.

Heezen and Tharp (1965) made the first major attempt to describe the physiography of the Indian Ocean. Their physiographic map revealed a great complexity about the Indian Ocean (Mckenzie *et al.*, 1971). They emphasized the active mid-ocean ridge system and the large fracture zones offsetting the ridge axis. Le Pichon (1968) incorporated among other data such observations and made the first attempt to apply the theory of plate tectonics in reconstructing the Indian Ocean.

Subsequently, further acquisition of geophysical data (Bathymetry, magnetic, seismic), in the ocean was advanced (e.g McKenzie and Sclater, 1971; Sclater and Fisher, 1974; Hales and Nation, 1973; Schlich *et al.*, 1974; Chetty and Green, 1977) to map the age of the ocean floor back to Late Cretaceous (75Ma). This data enabled McKenzie and Sclatter (1971) to be the firsts to incorporate magnetic anomalies data to reconstruct the northward drift of India to its present positon (McKenzie and Sclater, 1971; Sclater And Fisher, 1974). Unfortunately, the data did not go far back in time to warrant precise paleoreconstruction of the Indian Ocean.

Despite the advances made in data acquisition in the late 1960s and early 1970s, a critical question that still lingered as to the true initial geometry of Pangea. This was following the early debate between Wegener and du Toit. The position of Madagascar with respect to Africa was crucial in deciding the geometry of Pangea, which also has strong consequence on the rest of the East Gondwanian plates (Antarctica, Australia, Sri Lanka, and India) positioning relative to Africa.

Three possibilities were considered for the paleo-position of Madagascar (Figure 5);

(i) A position adjacent to East Africa, off the coast of Somalia, Kenya, and Tanzania as originally proposed by du Toit (1937) and later favored by Smith and Hallam (1970) and others. This proposal was based on the general lithological similarity of the lower Karoo successions in the northern parts of East Africa and western Madagascar and widespread marine transgression of the Middle Jurassic in both areas which form a strong argument for a paleo-position in the north (Dingle and Scrutton, 1974; Foster, 1975).

(ii) A position adjacent to Mozambique proposed originally by Wegener (1929) and supported with some geological arguments by Flores (1970, 1972) and Tarling (1972). Mainly based on the shape of the coastline of Madagascar and Mozambique, and the close relationships of Aptian faunas of southern Mozambique to that of Madagascar, and some similarities in the late Paleozoic (lower Karroo) history between the two domains (Flores 1970, 1972; Tarling, 1972; Dingle and Scrutton, 1974; Foster, 1975). The biggest hindrance to this hypothesis was the excessive Karoo volanism in Southern Africa and Mozambique in the Jurassic, which is not present in Madagascar. This phenomenon could not be explained by the proponents of this initial fit between the two plates.

(iii) A proposition that Madagascar stayed in its present position since the Paleozoic (Francis *et al.*, 1966). Proponents of this hypothesis assumed a possible seaward extension of the East Africa Karoo Series into the Indian Ocean between Kenya and Seychelles Islands (Dixey, 1956; Tarling, *et al.*, 1972). Such stratigraphic interpretation assumes the western part of the Indian Ocean to be underlained by non-oceanic crust, implying the Mozambique Channel as a continental geo-synclinal structure (Dixey, 1956), contradicting current knowledge.

McElhinny *et al.* (1976) presented new palaeomagnetic evidence in favour of the fit of Madagascar against Tanzania-Kenya margin; so that Madagascar's position relative to East Africa within Gondwana became generally regarded as correct (Powells *et al.*, 1980), ending the debate between Wegener and du Toit.

Since the early 1990s more gravity, bathymetry and altimetry data (Smith and Sandwell 1997; Sandwell *et al.*, 2014) have been acquired and published (Figure 4), providing significant knowledge on the structures in the Indian Ocean, and greatly improving our understanding of the evolution of the ocean. However, the question of the positions of the plates within Gondwana is still not resolved. Fortunately, the constraining of the plates can now be improve from recent offshore and onshore geophysical (Gravity, magnetic, bathymetry etc…) and geological (basement geology, sediment and volcanic record etc...) surveys, granting better constraining of Gondwana's initial fit and evolution.

1.4 COMPARING PREVIOUS RECONSTRUCTION MODEL

There are several approaches that can be adopted in reconstruction modeling
Here we discuss four of these approaches to understand why they are characterized by large differences.

Fits based on morphology

The initial reconstruction models (e.g. Wegener, 1929, and du Toit, 1937) were based on visual matching of continental coastlines. The key consideration in models that pursue this approach, is how best the morphology of the continent can be fitted to each other. Snider-Pellegrini (158) model for Africa and South America was based on this method. Wegener (1929) and du Toit (1937) later followed the same approach, proposing models primarily base the morphology of the continents. The method largely relies on the shapes of the coastline. Examples include; (Wegener (1924) and du Toit (1937).

Fits based on magnetic anomaly and fracture zone

This method involves matching conjugate anomalies and tracing back the plate's trajectory following the seafloor fabrics. Latitudinal and longitudinal displacement of the plates are constrained by a set of poles taking into consideration the seafloor lineaments (Fracture zones) and the magnetic anomaly data. Recent gravity and altimetry data from Sandwell and Smith (1992, 2014) has enhanced the accurate tracing and matching of these seafloor lineaments, thus improving the constraining of the evolution. The challenge with this method lies in the accurate determination of the seafloor record (especially the magnetic anomalies) close to the continental margins. The records are poor close to the margin due to the huge sediments obscuring the data leading to ambiguities in the reconstruction. Example include: Norton and Sclater, 1979; Martin and Hartnady, 1986; Powell *et al.*, 1988; Sandwell and Smith, 1992.

Fits based on geology

The approach here is based on identification and juxtaposing of rocks and crustal bodies with similarities in age and geochemical signatures. These similar rocks together with marked shear zones align to their conjugates across the plates. The key in this method is the similar characteristics of the rocks (Age, geochemistry, stratigraphy and structure) under consideration. Examples include Flores, 1970; Ricou *et al.*, 1990.

Fit based on combination of onshore and offshore geophysical and geological data including the shape and nature of the continental margins.

This approach adopts integration of on-land and offshore geological and geophysical data including on the continental margins to constrain the evolution of the plates (Aslanian *et al.*, 2009, 2012; Moulin *et al.*, 2010). It involves analysis and interpretation of geophysical (seismic, gravity, magnetic, and bathymetry), and geological (Sediments and basement rocks) data from the adjoining plates in order to accurately juxtapose them. The seismic data are not only used for the geometry and the nature of the crust but also to constrain the vertical and horizontal movements independently. Such is the method applied in Sahabi et al. (2004), Moulin *et al.* (2005, 2010) and Aslanian *et al.*, (2009), along which lines this work was pursued. Examples include : Sahabi, 1993; Sahabi *et al.,* 2004; Moulin *et al.*, 2005, 2010, 2012; Aslanian *et al.*, 2009, 2012.

We present in the following section, examination of selected reconstruction models of the Indian Ocean, their underlying reasons and consequences and highlighting the step by step evolution. The position of the South America respect to Africa, although shown on the figures, will not be discussed, as it has been already analysed by Moulin *et al.* (2010a, 2010b) and Aslanian andMoulin (2012). The figures present the continents with their basement geology and the offshore geological and geophysical constraints that will be presented in the chapters 6 and 7

1.4(a) Smith and Hallem, (1970)

Smith and Hallem (1970) (Figure 6) refined the model propounded by du Toit (1937). They constrain their initial fit using both geological and seafloor magnetic and fracture zone records on conjugate margins. Their model presented a good reconstruction of the Gondwana based on of the data available at the time. However, the position of Antarctica leads to an overlap on the Falkland Plateau and the Beira High.
(Madagascar-India). Note the position of Antarctica, which does not overlap Africa and the Limpopo Basin in Africa.

1.4(b) Norton and Sclater (1979)

Norton and Sclater (1979) proposed loose initial fit of Gondwana (Figure 7). Their model was based on magnetic anomaly data of Ségoufin (1978) and sedimentary studies in the Somali Basin. They placed the Mozambique Ridge loosely between Africa and Antarctica, treating it as a pre-drift structure. The model left a ~200km of gap between Madagascar and India.

1.4(c) Powells *et al.* (1980)

The model Powells *et al.* (1980) was based matching of seafloor spreading lineaments (Fracture zones). They agreed with McElhinny *et al.* (1976) and the above models, that the western side of Madagascar flanked equatorial East Africa: observing the pattern of seafloor spreading between Madagascar and India they deduced that the southern half of the western margin of India could not fit alongside the eastern margin of Madagascar as was initial proposed in Smith and Hallem (1970), but must have lain farther south (Figure 8). Their model results in a very rough initial fit of Gondwana; a leaving a ~500km gap between India and Madagascar, and ~800km gap between Antartica and Africa.

1.4(d) Martin and Hartnady (1986)

The initial fit of Gondwana proposed in Martin and Hartnady (1986) (Figure 9) involves only Africa and Antarctica. **It change drastically the position of East Antarctica in placing it adjacent to the Lebombo Mountains, subparallel to the Sabi acid volcanic suite, and overlapping the Natal Valley.** They proposed that the North Natal Basin is underlained by oceanic crust or very highly extended continental crust.

They discussed three plate tectonics scenarios for the development of the Mozambique Ridge. Two of the scenarios considered the Mozambique ridge to be oceanic in origin, formed either entirely on the African side or, its southern end formed on the Antarctica side. The two scenarios implied existence of an east–west directed spreading centre between the Mozambique Ridge and Africa. Their third scenario assumes a continental origin for the ridge, linked between the Astrid Ridge, and the volcanic rocks of Lebombo and Nuanetsi.

They further proposed the existence of an extinct spreading centre northern Natal Valley. We will further analyse these interpretation in the light of new knowledge and new data acquisitions.

1.4(e) Sahabi (1993)

In this model, the constraint of the initial positions of the plates was achieved combining geological and geophysical data across the plates (Figure 10). It presents a very tight reconstruction. Contrary to previous model, and as we will see recent studies (Eagles and Konig, 2008; König and Jokat, 2010; Leinweber and Jokat, 2012; Seton *et al.*, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2015; Nguyen *et al.*, 2016), this model considers a continental origin for the Limpopo Basin, Natal Valley, and the South Mozambique Ridge, avoid overlap of the Antarctic plate across them, except on the Beira High. The fit of Madagascar relative to Africa is affected by juxtaposition of Mesozoic basins of Mombasa and South Tanzanian in Africa, and Majunga and Morondava in Madagascar. The model aligns the Batsimisaraka Shear zone; a structure which according to recent field studies by Tucker *et al.* (2014) is not evident, to the Moyar Cauvery Shear Zone.

1.4(f) Marks and Tikku (2001)

Marks and Tikku (2001) following the ideas of Martin and Hartnady (1986), proposed a fit for the Madagascar, Africa and Antarctica plates. In their model, the Mozambique Ridge behaved like a microplate with its own independent motion between anomaly M11 and M2. Their proposed model results in a large overlap of about 200km of the northern part of the ridge on the Africa continent (Figure 12). To the North, Madagascar overlaps Africa for more than 100km.

1.4(g) Tikku *et al.* (2002)

One year later, Tikku *et al.* (2002) (Figure 13) suggested the existence of an active spreading centre between the Mozambique Ridge and the African continent (in the NNV), and considering Mozambique Ridge accreted as microplate between magnetic anomaly M11 and M2 (133–124 Ma). Their model results in an overlap of the Mozambique ridge across the NNV and Antarctica in the initial fit and a gap of more than 800km on the Zambezi area.

1.4(h) Jokat *et al.* (2003)

The model in Jokat *et al.* (2003) presented new view of the Limpopo basin (Figure 14). This mùodel based 1) on aeromagnetic data sets offshore Dronning Maud Land (Antarctica) and 2) linked to the plume paradigm, which was preeminent at that time. They proposed the formation of first oceanic crust in the Riiser Larsen Sea-Mozambique Basins around M25 (155 Ma) (the age of the oldest true magnetic anomaly between the two basins). They argued that the Karoo and Dronning Maud Land magmatism occurred well before (the volcanism started as early as 200 Ma, 193 Ma, 178 Ma, 165 Ma, 150 Ma, through to 137 Ma) any new ocean floor was created in the Indian Ocean, and therefore the first oceanic crust in the ocean cannot be related directly to any plume event. They further argued that the Explora Escarpment (EE) cannot be linked as direct conjugate of the Lembobo monocline, as a 190-180Ma age cannot be confirm for the EE by their magnetic data, and in agreement with ODP drilling (ODP Sites 692 and 693), they interpret the EE to have formed between 150-138 Ma, contrary to an overall age of 180 Ma proposed in previous models.

They noted that since the initial volcanism in Africa occurred between 200-180Ma (40-20Ma before the first identified oceanic crust formed), the large time delay between the volcanic event and the initial separation of Africa and Antarctica indicates that this plume event did not provide the essential trigger for the breakup of Gondwana, but may have controlled the ultimate positioning of major fault systems within the supercontinent, which may have subsequently been exploited to disaggregate the supercontinent.

1.4(i) Konig and Jokat (2006)

Following Marks and Tikku (2001), Konig and Jokat (2006) (Figure 15) proposed extinct spreading centre in the North Natal Valley (NNV) and discussed the existence of an independent Mozambique ridge microplate prior to 120 Ma. They proposed independent development for the Somali Basin, the Mozambique Basin–Riiser-Larsen Sea, and the Weddell Sea Basin after the breakup of Gondwana. They proposed that the first oceanic crust in the Riiser-Larsen Sea and Mozambique Basin at M24 (155 Ma), and in the Somali Basin, dated at M22 (152 Ma) (according to Segoufin and Patriat, 1980, and Cochran, 1988) or possibly M25 (157 Ma) (according to Rabinowitz *et al.*1983). In the Weddell Sea, the opening started at around 147 Ma in the southernmost part. Their model results in an overlap of the Mozambique Ridge in the Limpopo Basin in the initial fit of Gondwana.

1.4(j) Eagles and Konig (2008)

The model of Eagles and Konig (2008) followed the two previous ones (e.g Jokat et al., 2003, Konig and Jokat, 2006,) and is also based on aeromagnetic data off the coast of Antarctica (Dronning Maud Land).

These authors assumed oceanic origin for the entire Mozambique ridge, and the Southern Mozambique plains, thus disagreeing with Marks and Tikku (2001) who had earlier described the Mozambique ridge as a microplate, and proposed independent motion for it. They predicted breakup around 183-177Ma to coincide with the Karoo volcanism, and proposed the Lebombo and Mateke-Sabi monoclines, and the Mozambique and Astrid ridges as two sets of conjugate volcanic margins, considering the Agulhas Plateau and Maud Rise are parts of a dismembered large igneous province. The model results in a larger overlap of Mozambique Ridge across the Limpopo Basin, and the ~700km overlap between India and Antarctica, which it places Sri Lanka in the Enderby Basin (Figure 16). Their position of Sri Lanka in their model was not adequately constrained as it lacked geological and geophysical.

1.4(k) Konig and Jokat (2010)

Konig and Jokat (2010) assumed an oceanic origin for the Mozambique Ridge. In their model, the emplacement of the ridge occurred between 140-120Ma as a result of long lasting volcanic activity (140-120Ma). The flowlines for Antarctica proposed in their model crosses the magnetic spreading anomalies in the South Natal Valley (SNV), and thus implies the SNV to have formed between Africa and Antarctica (Figure 17). This is in contradiction to the pattern of spreading anomalies in the SNV (Goodlad *et al.* 1982). The model results in ~130km overlap between Antarctica and Africa.

1.4(l) Seton *et al.* (2012)

Reconstruction model of Seton *et al.* (2012) adopted a model for Gondwana whereby pre-breakup margin extension was initiated at 180 Ma as a response to thermal weakening by the eruption of the Karoo flood basalts, and initiated seafloor spreading at 160Ma along the entire East Africa margin, about 5million years before the earliest confidently dated magnetic anomaly M25. Together with Torsvik *et al.* (2012), they reconstructed Antarctica with an overlap on the Beira High, NNV, N Mozambique Ridge, and Limpopo basin (Figure 18).

1.4(m) Torsvik *et al.* (2012)

Torsvik *et al.* (2012) used palaeomagnetic, seafloor magnetic and fracture, and supposed hotspot tracks data to restore the plates to their initial positions in Gondwana, with less consideration on the Margins. Their model like Eagles and Konig (2008) Konig and Jokat (2010), Leinweber and Jokat (2012), Seton *et al.* (2012) and the following Gaina *et al.* (2013), Reeves *et al.* (2015), Nguyen *et al.* (2016), prefer Early Jurassic breakup for Gondwana, a period close to the Karoo volcanic event, and oceanic origin for the Limpopo Basin, Natal Valley, and the Mozambique Ridge. Consequently, such models allow Antarctica to overlap these structures and results in ~300km of overlap between the two continents (Figure 19). Their model further results in ~140km gap between India and Madagascar.

1.4(n) Leinweber and Jokat, (2012)

Following Cox (1992), Leinweber and Jokat (2012) considered the inner Explora Wedge (Antarctica) as the conjugate feature data to the Lebombo monocline (Africa). They proposed two distinct opening stages for the Africa and Antarctica corridor. Their initial fit of Antarctica with respect to Africa starts from a tight fit position, with a resulting ~300km overlap of Antarctica on Africa (Figure 20). Stage 1 involves an anticlockwise rotation of Antarctica with respect to Africa. They proposed the the rotation led to the formation of the southern Astrid Ridge near the southwestern limit of the Mozambique Belt as well as oceanic crust in the eastern part of the Limpopo Basin; and transitional crust in the western parts of the Limpopo and North Natal Valley. Antarctica took a southward orientation in drift from Africa during stage 2. The Riiser Larson Sea and the Mozambique Basin were finally opened at this stage.

Their work centred largely on constraining the initial fit between Africa and Antarctica. The predicted anticlockwise rotation of Antarctica impacted the rest of the East Gondwana, resulting in Compressional deformation between Madagascar and Africa (See also chapter 1.6, figure 26) before the subsequent strike-slip movement of Madagascar along the Davie fracture zone. The model is based on interpretation of magnetic anomaly M41 in the Zambezi Basin from (e.g Leinweber *et al*, 2013), without any corresponding anomalies in the conjugate basin, and assumption of an Early Jurassic Gondwana breakup linked to the Karoo volcanic activity. They further assumed an oceanic origin for the Beira High, Limpopo Basin, the North Natal Valley, and the Mozambique ridge, permitting a total overlap on them by Antarctica.

The proposed very tight position of Antarctica with respect to Africa impacted subsequent models.

1.4(o) Gaina *et al.*, (2013)

Following the interpretation of Leinweber *et al.* (2013), Gaina *et al.* (2013) assumed magnetic anomaly M41 (167.5 Ma, e.g; Grastern *et al.*, 2012) as the oldest Jurassic magnetic anomaly in the Somali and Mozambique basins, assigning assign breakup age of 170Ma in both basins. Note again that there is no evidence of similar magnetic anomalies in the conjugate basins.

They agreed with the interpretation of Seaward Dipping Reflectors (SDR) along the Mozambique coastal plains, as earlier propounded by Cox (1992). Their model like all the other models with this underlying assumption, results in overlap of Antarctica over the Beira High, the Limpopo Basin and the NNV (Figure 21). The model further results in ~250km overlap between India and Antarctic, an overlap of ~100km between Madagascar and Africa and ~140km gap between India and Madagascar.

1.4(p) Reeves *et al.* (2015)

The reconstruction in Reeves *et al.* (2015) incorporates small distinct rotation poles for several Precambrian cratons and continental fragments to constrain the initial configuration of Gondwana. The cratons and continental blocks are juxtaposed to their conjugates, with a permitted distance of 60-120 km between them. This distance representing the amount of Precambrian crust presumed now stretched into rifts and passive margins. Their model may work less well for wider de-stretched and highly extended margins, as the true extent of extension between most of these Precambrian units remains speculative. To examine the implication of Reeves *et al.*, (2015), we worked with the coastline of the plates and the poles provided in the model (Figure 22). This model results in ~300km of overlap of Antarctica on the African plate (in the Limpopo Basin) and in an overlap of the same order of Madagascar on Africa. Antarctica completely overlaps the Beira, the Mozambique and the North Natal Valley as the last previous models.

1.4(q) Nguyen *et al.* (2016)

Nguyen *et al.* (2016) adopted the poles of Gaina *et al.*, (2013) for the initial fit of Madagascar relative to Africa, and Seton *et al.* (2012) for the rest of the East Gondwana plates (Figure 23). Their model, as in Gaina and Seton, links breakup Gondwana close to the Karoo event, implying 20-30 Ma disintegration of Gondwana before the oldest magnetic anomaly was recorded. No adequate explanation was given for such delay. Furthermore, their model implies oceanic origin for the Mozambique and Madagascar aseismic ridges.

Their model also results in ~150km overlap of the India plate over the Antarctic plate, and ~140km gap between India and Madagascar. Note the very southern position of Madagascar which produces overlap on Africa, does not correctly link the southern shear zones of Madagascar with their counterparts in Tanzania + North Mozambique.

1.4(r) Phethean *et al.* (2016)

Phethean *et al.*, (2016) proposed new spreading lineaments in the Somali Basin, based on directional derivatives of free-air gravity anomalies in support of a tight fit of Madagascar to Africa (Figure 23) following Reeves and de Wit. (2014). Their spreading lineament was achieved through band-pass filtering of Sandwell *et al.* (2014) gravity data. The methodology adopted in their work produces possible artificial structures and lineament within the Somali basin. They presented a short seismic reflection profile across the Davie and generalized their interpretation for the whole ridge. In their model, the ridge is interpreted as an ocean-ocean fracture zone formed by a coalescence of several small fracture zone during the evolving motions of Madagascar from Africa.

Their initial position of Madagascar (Figure 23) has serious consequences on the position of Antarctica and the rest of the East Gondwana (India, Sri Lanka, Australia), as it implies an inward position of Antarctica taking into consideration current constrains and holding fixed the Antarctic-Madagascar-India-Sri Lanka-Australia plate circuit. This leads to Antarctica overlapping the African plate by over 350km in the Limpopo Basin, and on the Mozambique Ridge and North Natal Valley, as seen in Reeves *et al.* (2015). Consequently, a way to avoid the overlap of Antartica on Africa, will be to define an independent early drift motions for the Somali Basin different from that of Mozambique Basin.

Since 2003, the overlap of Antarctica on the Limpopo Basin, the Beira High and the Natal Valley is more or less a constant in many the published models.

1.5 MODEL CONSEQUENCES

Detailed kinematic reconstructions of the Indian Ocean present lots of challenges. This phenomenon is as a result of the numerous unanswered scientific questions in the ocean due to inadequate data, and in some cases lack of consensus on the interpretation of available data, this led to inconsistent and incoherent kinematic models characterized by large gaps and overlaps between Gondwanian plates.

Figure 25 presents two focal points of figure 2,that highlights four models: Sahabi (1993) Leinweber and Jokat (2012); Gaina *et al.* (2013); Reeves *et al*, (2015).

- Figure 25(a) shows the relative position of Madagascar to Africa in these four models. Notice how Madagascar is differently placed in all four models in terms of latitude and angle.
- In the models of (Sahabi, 1993; Leinweber and Jokat, 2012; Reeves *et al.*, 2015), Madagascar is fitted more angular to Africa, as opposed to that of Gaina *et al.* (2013) in which it is relatively north-south. Notice the angular and latitudinal position of Madagascar has strong implications on the position of the rest of Gondwana's plates relative to Africa, and therefore very crucial to Gondwana's initial configuration. It also calls into question the nature of crust underlying the overlapping areas and the conjugate basins of Morondava and Majunga in Madagascar.
- For the fit between Africa and Antarctica (Figure 25b), the models, Leinweber *et al.* (2012), Gaina *et al.* (2013), and Reeves *et al.* (2015) all overlap the African tectonic plate across the Limpopo basin, and thus supposed an oceanic origin for the basin. Note that this position of Antarctica is not coherent with the overall segmentation of the area (Figure 2) and will imply very complex evolution in order to explain the clear alignment of the straight Limpopo margin and the Fracture Zone Fracture on the south (black dotted line in figure 2). Contrary to these three models, Sahabi (1993) avoids this overlap, and consider the basin to be continental in origin calling into question the crustal nature and age of the Limpopo basin and spreading regime leading to its formation. We will see in chapter 5 that new seismic refraction data interpretations in the Limpopo Basin confirm the basin to be continental in origin (Moulin *et al.*, submitted, Lepretre *et al.*, 2017; Verrier *et al.*, 2017),. Other critical questions that still remain unanswered include: the origin of Gondwana's breakup, the age range of the rifting, the position of the Continent-Ocean Transition Boundary in Mozambique basin,

the first oceanic crust in Mozambique basin; and the crustal nature of the Mozambique and Madagascar aseismic ridges.

Additionally, widely differing opinions exist on the assumed path ways along which these fragments have reached their present locations (e.g Smith and Hallem, 1970; Tarling *et al.* 1972; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber *et al.*, 2012; Seton *et al.*, 2012; Torsvik *et al.*, 2012, 2008; Gaina *et al.*, 2015, 2013, 2007; Reeves *et al.*, 2002, 2014, 2015 figure 26 and 27).

- The Leinweber *et al.* (2012) model implies an early compression, and Reeves *et al.* (2015) start with an initial overlap of Madagascar on Africa between 180Ma to 160Ma before it begins a southward drift to its present position. That of Gaina et al. (2013) takes a more Southeast drift throughout its evolution to its present position, whilst the model of Sahabi begins first with an initial short southeastward movement and a subsequent southward drift (Figure 26).
- The evolution of Antarctica with respect to Africa (Figure 27) for the four models begins with a southeast motion, followed by a south drift. The motions are not significantly varied, except that the initial motion in Gaina *et al.*, (2013) is relatively zig zag. Notice also that Gaina *et al.*, (2013) and Leinweber and Jokat, (2012) and Reeves *et al.* (2015), all starts from an initial overlap across the Limpopo Basin. Only the
  Sahabi's Model can describe a simple clear alignment of the straight Limpopo margin and the Fracture Zone Fracture on the south (black dotted line on Figure 2)

CHAPTER 2: SCIENTIFIC QUESTIONS

Chapter 2

2.1 SCIENTIFIC QUESTIONS

Notwithstanding the many dedicated effort to constrain the initial configuration of Gondwana over the past five decades, the question of the "original geometry of Gondwana'' and how it disintegration is still not resolve (see the review in Chapter 1). A phenomenon that has led to varied and complex models of the Indian Ocean whose underlying reasons raises lots of questions. I discuss here some of the unanswered questions in the Indian Ocean, responses to which are very critical to unraveling the initial of reconstruction of Gondwana, and the subsequent evolution of the Indian Ocean.

2.1(a) What is the origin of the Karoo volcanism?

The continental Karoo basins (Upper Carboniferous-Permian to Triassic) extends from the South of South America to India, through the South of Africa, Antarctica and Madagascar. Some of them are sealed by an important magmatic event, called the Karoo Traps (ca 183-179 Ma) (Figure 28). The origin of this Karoo volcanism is still widely debated among researchers. Three sources have so far been proposed for this event.

1. Plume (Burke and Dewey, 1973; Cox, 1992; Duncan *et al.*, 1997), implying deep mantle source for the magma.
2. Enriched upper asthenospheric upwelling or a lower continental mantle as suggested by (Bristow, 1983; Klausen, 2009; Hastie et al., 2014), implying much shallower source.
3. Lower mantle source for the magma. (Torsvik et al. 2012).

The plume hypothesis was based on proposed triple junction in Southern African [the junction of the Nuanetsi-Save, Tuli and Lebombo basins (Figure 28)], which is argued (Cox, 1992; Duncan *et al.*, 1997) to have resulted from an upwelling mantle plume (Duncan *et al.*, 1997). Secondly, that the evolution of the magma particularly on the Lebombo monocline, from nephelinites, to picrites, to basalts, and finally rhyolites (high to low Ti), can best be explained by a gradual progression from primitive to tholeiitic magma compositions (Klausen, 2009). However, two comments are pertinent 1) nephelinetes are high pressure-low temperature magmas whose source is different from the high temperature low pressure magma of picrites; 2) the evolution of the magma from picrites to rhyolites does not necessary warrant continent breakup. Such evolution is governed by complex fractional crystallizations processes, that are controlled by the duration and interaction of the magma with the lithospheric crust or mantle (e.g Bristow 1980), changes in partial pressure and temperature, and addition or loss of other chemical fluids such as water, oxygen, carbon dioxide and hydrogen.

In addition, the Karoo magma lacks comparable compositions of primitive plume magma (Riley *et al.,* 2005; Hastie et al., 2014). For a plume source, they should have high $^{3}He/^{4}He$ ratios, if their source has an origin in the lower mantle, which for now there is no data to confirm such high ratios (Bristow, 1980; Hastie et al., 2014).

The asthenospheric or enriched continental mantle source for the Karoo volcanics (Bristow, 1980; Klausen, 2009; Hastie et al., 2014) argue on the base of the long duration of the Karoo event, lasting about 10Ma (Klausen 2009; Hastie et al., 2014), compared to mostly short lived 3-5Ma for plumes (Hastie et al., 2014).

Bristow, (1980) observed that the Karoo basalts show both enriched and depleted mantle sources and therefore predicted that these basalts have being sourced differently (See also figure 29). He also observed that the rhyolites show abnormally high Sr and Ba components, with high enrichment in K and Na compositions. He therefore predicted that these rhyolites may have been sourced from the partial melting of previously underplated basaltic magma that may have contaminated the magma leading to the high Sr, K and Na contents.

His work reinforces the concepted different source origins of the Karoo magmas, explaining the volcanic episodes as complex interactions of mantle stresses and the African lithosphere.

However, Svensen *et al.,* (2012) presented U–Pb zircon ages for the Karoo sills and dykes with the ages ranging from 183.0 ± 0.5 to 182.3 ± 0.6Ma, and emplacement rate of 0.78 km 3/yr, higher than previous estimates. Their results challenge the view that Karoo melt emplacement was a prolonged process and strengthens the hypothesis of single Larfge Igneous Province (LIP) magma event.

It is worth noting that in the Limpopo Basin, Natal Valley and Mozambican channel, the ongoing analysis of Total and Pamela seismic indicates multiple episodes of magmatism (Uppper Jurassic-Early Cretaceous, Turonian, Eocen, and Actual). Some so-called Karoo reflectors may have been misdated.

Thus answering question of the origin of the Karoo magmatism is importznt to determine whether it was due to a plume or the magma came from the lower continental mantle, and the role of the event in the beakup of Gondwana. Our goal here is to examine current geochemical data on the Karoo magmatism to determine whether it was a plume that caused the breakup of Gondwana.

2.1(b) What is the role of the Karoo magmatism in the breakup of Gondwana?

The African continent from the Permian to recent times has experienced varying magnitude of intraplate volcanism, most often centered along pre-existing fractures and faults zones within orogenic mobile belts along Archaean and Paleoproterozoic cratonic boundaries (Watkeys, 1998). Southern and eastern Africa are characterized by vast network of sills and dykes that are pre-syn-post Karoo volcanism (Hastie et al., 2014) (Figure 28). The Karoo event was also extended to Dronning Maud Land of Antarctica (Elliot and Fleming 2000, Burges et al., 2014), and is contemporaneous with the igneous rocks of the Ferrar Province (Antarctica, Elliot and Fleming 2000 and many others), and the intrusive components of Tasman dolerites in Australia. Studies of the dykes in the Dronning Maud Land, the Kirkpatrick basalts and the Tasman dolerites have been shown to have compositional and age overlaps with the Karoo granting some common history of their intrusion (Elliot and Fleming, 2000 and Klausen, 2009) except the Ferrar Province which was emplaced about 5-10Ma later in the Middle Jurassic [(Duccan *et al.,* 1997; Elliot and Fleming, 2000 (Figure 30)].

Workers are currently divided on the interpretations and the importance of the Karoo volcanic events to evolution of the Indian Ocean. Debates are still ongoing as to whether the event caused Gondwana's breakup or not. The Mbuluzi rhyolites and Rooi Rand Dykes (174Ma Ar/Ar; Klausen, 2009) of the Lembobo monocline is described as having Mid Ocean Ridge Basalt (MORB) like characteristics [Jourdan *et al.*, 2007; Klausen, 2009; Hastie et al., 2014, (figure 31)], and its emplacement coincident with the formation of first oceanic crust in the Mozambique Basin, almost 10Ma younger than than Karoo volcanism and about 20Ma older than the confidently dated oldest true magnetic anomaly in the basin magnetic anomaly M25. No reason has been given for such delays except the attempt to interpret weak magnetic signals within the Jurassic Quiet Zone to close the gap. Note also that the scheme proposed by Klausen (2009) corresponds to Landward Dipping Reflectors instead of the usual Seaward Dipping Reflectors.

The general succession of the Lebombo monocline starts with the Mashikiri nephelinites (183Ma Klausen, 2009) at its base overlaid by the Letaba picrites (183Ma Klausen, 2009) (Figure 31), which in turn are overlaid by Sabie River basalts (182Ma? Klausen, 2009), Jozini

Formation (174Ma Klausen, 2009), Mbuluzi rhyolites and Rooi Rand Dykes (173Ma Klausen, 2009), and basaltic Movene Formation successions (173Ma Klausen, 2009). The succession finally overlaid by younger Bumbeni complex (133±4Ma Allsopp *et al.*, 1984), a post Karoo intrusion.

The assumption of the Karoo igneous event (Mbuluzi rhyolites and Rooi Rand Dykes) to have resulted in the breakup Gondwana stems largely from the observed rapid increase in lava and dyke densities in the Lebombo toward the Limpopo Basin, as well as the global observation that silicic volcanism marks successful continental breakup (Jourdan et al 2007), and therefore the Karoo can be related in that sense.

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 if one suppose oceanic crust east of the Lebombo monocline in the Limpopo Basin; a basin whose crustal nature is still unknown. This assumption coupled with the undetermined source of the Limpopo Basin could potentially result in ~300km overlap or gap between Africa and Antarctica, depending on the interpretation adopted in the reconstruction modeling. It also implies a short period for the rifting event, ending in the Lower Jurassic (Geiger *et al.*, 2004; Klausen, 2009, Hastie et al., 2014).

In fact many of these models focus attention on resolving how tightly Antarctica can be fitted to Africa. Cox, (1992), Klausen (2009), Hastie *et al*, (2014), argued the conjugate of the Lebombo monocline to be the Explora Escarpment (EE) and the Explora Wedge, fitting the two together. Jokat *et al.* (2003), disagreed with this argument, noting that 190-180Ma age cannot be confirmed for the EE by their magnetic data, and therefore the EE cannot be juxtapose as direct conjugate of the Lebombo monocline. In addition, ODP drilling (ODP Sites 692 and 693) retrieved shallow water black shales of Valanginian-Hauterivian (Site 692, 138–124 Ma) and Albian/ Aptian age (Site 693, 110 Ma) that indicate shallow water and anoxic conditions at that time (Mutterlose and Wise, 1990; Jokat *et al.*, 2003). The large time delay between the volcanic event and the initial separation of Africa and Antarctica thus indicate the plume event, if it exists, did not provide the essential trigger for the breakup of Gondwana, but may have controlled the ultimate positioning of major fault systems within the supercontinent, which may have subsequently being exploited to disintegrate the supercontinent.

Thus answering the question of the role of the Karoo magmatism in the breakup of Gondwana is important to determine when the breakup of East-West Gondwana occurred and when the oldest ocanic crust formed. Therefore, our goal here is examine pubished and new data on the Karoo magmatic event to determine whether it caused the breakup of East-Wzst Gondwana and initiated the oldest oceanic crust in the Indian Ocean.

2.1(c) what is the age range of the rifting, and when did the breakup occur?

The breakup of Gondwana was preceded by a long rifting and volcanic event (Flores, 1964 and 1975, 1980, Salman and Abdula, 1995), the range of which is debated (See the charts in figure 32, 33 and 34). Three schools of thought currently exist on the rifting and breakup of Gondwana based on geological and geophysical studies. One school of taught proposes a short rifting event terminating in the Karoo plume event in Southern Africa (Cox, 1992) and the Toarcian Andafia Formation in Madagascar (in that the Andafia beds indicate the first major marine incursion in the Somali Basin, and therefore implies oceanization). The second proposes a much longer span of Gondwana rifting, continuing after the Karoo volcanic event; the rifting affecting the Belo continental sediments that overly Karoo volcanics (Flores, 1964; Salman and Abdula, 1995, Salazar *et al.*, 2013) based on seismic reflection data in Mozambique Basin, and Duvalia marls and mudstone in Madagascar (Figures 33 and 34). The third school of tought suggest two-phase of breakup (Cox, 1992, Mahanjane, 2012). Working on multichannel seismic reflection data in the Zambezi Basin, they propose several rifting events: a first early

Jurassic stage of rifting terminating with the Karoo magmatism that induced Gondwana's breakup and the creation of oceanic crust in the Zambezi depression and west Limpopo basins; second stage starting with a rift jump to initiate rifting between the Beira High continental crust (Muller et al., 206) and Antarctica in the Zambezi Basin leading to the accretion of the first true oceanic crust in the Mozambique Basin at magnetic anomaly M25 or M26. Offshore Zambezi Depression, lava flows may be associated with the emplacement of thick sequence of dykes during post-rift magmatism that occurred when the Antarctica Plate (with the Beira High) drifted relating from the west to east until the Mid-Jurassic times during Gondwana breakup first early stage.

During the early stages of exploration in the Mozambique Basin, several wells drilled in the basin that bottomed in basalts were interpreted as''Top Karoo Volcanics''. However, some K/Ar age dating (Flores, 1975, 1980; Salman and Abdula, 1995), although old data, showed very different ages for these magmatism thought to be Karoo (Figure 36).

Determining the age range of the rifting event in Gndwana is important to know when the rifting finally stopped and when the breakup of East West Gondwana occurred. Our main objective here is to study sedimentary and seismic data along the East African margin to determine the age range of the rifting event and the beginning of oceanization.

2.1(d) What is the nature of the crust underlying the Limpopo Basin?

The true nature of the crust underlying the Limpopo basin remains unresolved as to wether the basin created after the Karoo volcanic event, or whether instead of a continuous sheet of Karoo magmatism spreading eastward into the ocean from the Lebombo Monocline, the basin is characterized by the existence of a series of parallel, trending fractures (Figure 35) issuing ever younger magma from west to east (Flores, 1975).

Cox (1992) and Klausen (2009) identified ***Seaward*** (sic) Dipping Reflectors (SDR's) in the basin, which is assumed to continue westward.

The cause of this interpreted SDRs is also debated. Cox (1992) proposed the basin's development was related to a plume event, which resulted in suppressed breakup, extensive volcanism, and subaerial spreading in the Limpopo Basin. The event he proposed also led to the emplacement of the Explora Wedge (e.g. Hinz, 1981), deem conjugate to the Lebombo monocline. Storey *et al.* (1995), however, believed that the Karoo plume only played an indirect role in break-up of Gondwana by thermally weakening lithosphere and inducing local rifting but not resulting in breakup between Africa and Antarctica, this proposal may imply that crust underling the Limpopo Basin is not oceanic.

The observations of Cox (1992) and coworkers, contradicted Salman and Flores work, in the 1970s and 80s based on seismic and geological data in Mozambique Basin. They proposed the Limpopo Basin to be underlain by continental crust.

We will see that our own analysis of seismic data in the basin reveals old sedimentary sequence in the basin that could be ascribed to Karoo sediments, in agreement with the observations of (Flores, 1964, 1975, 1980; Salman and Abdula, 1995), or younger.

Applying seismic ambient noise tomography in the basin, Domingues *et al.* (2016) observed low crustal velocities along with a thinning of the crust. They interpreted a possible continental crust, with thickness between 20 and 30 km.

Theoretically, the assumption of oceanic crust in the Limpopo Basin has serious implications for the evolution of the Indian Ocean. It implies a short span of Gondwana rifting, and a sharp narrowing of the continent–ocean transitions in the Mozambique Basin. The overall consequences of all these debates are a possible large overlap or gap could be implicated in the geodynamic model.

Hence the answer to the question of the crustal nature of the Limpopo Basin is important to avoid the possible overlap or gap that could be implicated in the reconstruction models. We therefore examine published and newly acquired seismic reflection and refraction data in the Limpopo basin to ascertain its crustal nature and to propose a model coherent with the crustal nature of the basin.

2.1(e) what is the age of the first magnetic anomaly in the Indian Ocean?

The age of oldest magnetic anomaly that can be associated with first oceanic crust in the Mozambique basin is strongly debated. Segoufin (1978) and Simpson *et al.* (1979) published the earliest identification of seafloor spreading magnetic anomalies in the Mozambique Basin between M0r to M22. König and Jokat (2010) extended the identifications to M26n (close to 22°S 37 in the Zambezi Basin), and M22r as oldest anomaly in the area north of the island of Bassas da India, based on new magnetic data set of Jokat (2006). Their compilation was based on the magnetic survey of the MoBaMaSis project (Mozambique Basin Marine Seismic Survey) conducted in 2007. Leinweber *et al.*, (2012) combined the MoBaMaSis data, data from AISTEK II cruise (Jokat, 2006), and old ship data from the NGDC database, and re-picked the anomalies in the basin. Their picks confirm the initial picks of König and Jokat (2010), but they extended the identifications from M26 to M41 (Figure 37), shifting the Continent-OceanTransition (COT) about 150km shoreward. This implies that oceanization occurred earlier in the Mozambique basin than previous thought, and that, corresponding older seafloor spreading magnetic anomalies could be identified in the conjugate Riiser Larson Sea. The oldest magnetic anomaly identified in the Riiser Larson Sea, following a dense aeromagnetic survey, is anomaly M25 (Konig and Jokat, 2010) (Figure 37). No conjugate M41 was identified. This absence of anomalies older than M25 in the Riiser Sea may be explained by a ridge jump in the Zambezi Basin before anomaly M25, leaving the conjugate set of anomaly older then M25 in the Zambezi side. Currently, there is no evidence of such ridge jump in the Mozambique basin. Furthermore, the relative distance between the conjugate anomalies M25 to their shorelines is similar, which make the ridge jump hypothesis redandent. Note furthermore that anomaly M28 borders the

Beira High, and the presence of older magnetic anomalies as it is believe to exist in the eastern part of the Basin, will implies an oceanic nature for the Beira High.

We will present comparison of events in the Indian Ocean to its surrounding oceans in chapter 5.1(g). These oceans were opened and operating before Gondwana's breakup. We compare the impact of tectonic activities across Gondwana in these surrounding oceans to stimulate a global picture of the events, and to ascertain the impact of anomaly M41, and M25. Our observation indicates that M25 is a major event that affected all the surrounding oceans, but there was no record or impact of the M41 in any of the surrounding oceans although they were fully functional at that time.

The age of the first magnetic anomaly in the Indian Ocean has implication on the evolution of East-West Gondwana, the time of breakup and the age range for the rifting in Gondwana, and thus it determination is crucial. Our main objective here is to examine the published magnetic identifications in the Indian Ocean and compare them to records of major tectonic events in the sourrounding oceans to examine whether the accretion of the first oceanic crust proposed in published work ever impacted the surrounding oceans. We believe that a major event like the breakup of E-W Godwana will at least impact the surrounding oceans.

2.1(f) Where is the Continent-Ocean Transition boundary in the Mozambique Basin, what is the nature of Beira High aseismic ridge, how much gap is necessary for its accommodation?

The association of the Karoo volcanism with Gondwana's breakup and the interpretation of anomaly M41 imply that the Continent-Ocean Transition Boundary (COTB) may lie close to the Lebombo monocline, and about 150km shoreward from the boundary identified in Raillard, (1990) in the Zambezi Basin (Figure 37) they implies an oceanic origin for the Beira High. Furthermore, it results in sharp narrowing of the COT in the Zambezi basin, implying a short period for Gondwana rifting.

The Beira High is approximately 280 km long and 100 km wide (Mahajane, 2012), elongated in northeast-southwest direction subparallel to the Zambezi coastline. It is located in water depth between 1000 to 2500m, and buried by Mesozoic and Cenozoic sedimentary sequences (Mahajane, 2012; Muller *et al.*, 2016).

Following Leinweber and Jokat (2012), who identified older magnetic series (M29 to M33) on the Beira High, recent kinematic models (Gaina *et al.,* 2015, 2013; Reeves *et al.,* 2015; and Nguyen *et al.,* 2016) proposed models that lead to Antarctica overlapping on it, and therefore assumed oceanic origin for the High.

The question of the nature of the Beira High aseismic ridge and the Zambezi depression was controvercial until Muller *et al.,* (2016) (Figure 38), they presented seismic refraction and gravity data across the High and the depression, and interpreted the High to consist of continental crust, and the depression to be underlained by possible stretched intruded continental crust.

Consequently, according to the results of Muller *et al.* (2016), all reconstruction models overlapping Antarctica on the High may have to be adjusted (Figure 38c).

The seismic refraction results of Muller et al. (2016) is taken into consideration in this work to propose a new model that avoids overlap across the High and leaves sufficient space between Antarctica and Africa for its accommodation. We compare in chapter 6.2 the consequence of published models (Sahabi, 1993; Leinweber and Jokat, 2012; Torsvik et al., 2012; Seton et al., 2012; Gaina et al., 2013; Reeves et al., 2015; Nguyen et al., 2016; Klimbe and Franke, 2016; Davis et al., 2016) on the Beira High.

Our main objective here is to propose a model coherent with seismic observations of Muller et al. (2016) on the Beira High, allowing adequate space for it accommodation.

2.1(g) what is the true nature of the Mozambique and Madagascar ridges, and their impact on the reconstruction of the Indian Ocean?

The Mozambique and Madagascar ridges respectively terminate the western and eastern ends of the channel of the Mozambique basin (figure 39). The Mozambique ridge is formed of several bathymetric plateaus rising up to 3500m above the ocean floor. It has broad, elevated topography especially on its southern half, falling away steeply into the Mozambique basin to its east, and truncating sharply at its southern end (Gohl *et al.,* 2011). It separates two Mesozoic ocean basins that formed at two different spreading regimes [The Lower Cretaceous South Natal Basin (Goodlad, 1982), and the Upper Jurassic Mozambique Sea (Ségoufin, 1978; Simpson *et al.,* 1979; Sahabi, 1993)]. The Madagascar Ridge on the other hand, is ~400 km across, extending southwards from the southern end of the Madagascar continent for a distance of 1300 km. The ridge protrudes at water depth between 2000 and 3000m across most of the plateau.

The nature of the Mozambique and Madagascar ridges has large impact on the reconstruction modeling of the Indian Ocean. An oceanic nature implies they were created after Gondwana's breakup, and therefore could be overlapped in the initial reconstruction. A continental origin, implies their links to Gondwana crust and therefore cannot be overlapped in the reconstruction of the supercontinent. For instance, Figure 38c shows two reconstructions (Leinweber and Jokat, 2012 and Sahabi, 1993). Notice Leinweber and Jokat (2012) overlap Antarctica on the Mozambique ridge, and overlap the Madagascar ridge across the Africa continent assuming oceanic origin for the two ridges. Sahabi (1993) on the hand considering the north Madagascar ridge continental in origin allows space for its occupation in the fit, and avoids the overlap of Antarctica on the Mozambique ridge.

Therefore, the nature and origin of the two ridges has been under debate for a long time (Schlich *et al.,* 1974 and Goslin *et al.*, 1981; 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).

Dredged samples of Archean anorthosites, gneiss and metagabbros were retrieved along the eastern sector of the Mozambique Ridge during DSDP 249 (Ben-Avraham *et al.,* 1995), sharing similarities with Archean rocks of Zimbabwe craton (Tucholke *et al.,* 1981; Ben-Avraham *et al.,* 1995). Additionally, the metamorphic rocks show garnet-bearing metapelites and well-developed gneissic layering, interpreted to be similar to those found in the Namaqua-Natal belt of Southern Africa (Ben-Avraham *et al.,* 1995). This means a part of the Mozambique craton could have been broken off the Rhodesian craton or the Namaqua-Natal belt. The dredge samples consisted of metamorphic rocks as well as fresh quenched glasses of basalt with no significant alteration (Ben-Avraham *et al.,* 1995). The origin of the young volcanics remains somewhat unclear, since a part is of MORB-like character, while other parts fall outside oceanic basalt category (Ben-Avraham *et al.,* 1995). Chetty and Green, (1977), conducted seismic refraction studies across the Mozambique ridge. They proposed a Moho depth in excess of 22km based on isostatic equilibrium when compared with the adjacent Transkei Basin and Agulhas Plateau. However, their Moho depth of 22km is not a sufficient criteria to characterize the ridge as oceanic or continental. Fortunately, recent seismic refractions expedition in the Mozambique Basin during PAMELA-MOZ3-5 cruise, found the North Mozambique Ridge

(NMR) to consist mainly of sediments on a thinned continental crust (Lepretre *et al.,* 2017; Moulin *et al.,* submitted). Gohl et al. (2011) provided seismic refraction evidence in support of the southern Mozambique ridge having oceanic origins and possibly formed due excessive volcanism at a triple junction.

The Madagascar ridge was first considered continental extension of south of Madagascar by (Heezen and Tharp, 1966).

DSDP 246 and 247 attempted to determine the nature of the ridge but could not reach basement due to hole instability (Schlich *et al.,* 1974). Goslin *et al.,* (1981) presented seismic refraction evidence in support of an oceanic an origin for the southern part of the ridge. They proposed a subdivision of the ridge into two distinct domains (north and south domains). Their calculation of the depth of the Moho from the seismic refraction profiles showed that the thickness of the crust varied from south to north. In the southern part of the ridge, south of 32°S, the Moho is located at 14 km (Goslin *et al.,* 1981). Between 32°S and 30°S, it is located at a depth of 22 to 26 km (Recq *et al.,* 1979; Goslin, 1981). Their data did not extend north of 30°S, and therefore, the Moho in this area is unknown. Goslin *et al.,* (1981) prefered to interpret it as strongly anomalous oceanic crust.

Currently, the nature of the northern part of the ridge is undetermined (see figure 38). 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 spot. Goslin and Patriat (1984), consider south Madagascar ridge as conjugate to the the Crozet plateau formed along the South West Indian Ridge (SWIR) at Anomaly 24 (53.34Ma).

The reconstruction models of Smith and Hallem (1970), Norton and Sclater (l979) and Sahabi, (1993), leave large gap in southern Madagascar filled by the northern part of the Madagascar ridge, assuming continental origin.

We examine the consequence of published models on the Mozambique and Madagascar ridges, and use the new and published data on these two ridges to propose our new model.

2.1(h) Role of the tectonic structure of the basement in Gondwana's breakup?

At least three orogenic episodes can be recognized along the East African continental margin from Paleoproterozoic to present.

1. The Paleoproterozoic (2.2Ga-1.8Ga) that led to the formation of the Ubendian, and Usagaran belts (Daly, 1989; Reidel et al., 2014; Tucker *et al.,* 2014 and Rekha *et al.*, 2014).
2. The Mesoproterozoic (1.1-0.75Ga) establishment of the Kibaran belt, the ChomaKaloma block (CKB), the Natal belt, the Rehoboth belt, Namaqua belt and the Maud belt of the Dronning Maud lands Antarctica (Jacobs *et al.,* 2003, 2006; Bigen *et al.*, 2009; Reidel et al., 2014).
3. Neoproterozoic (650-550Ma) established the East African orogenic belt, the Neoproterozic orogenic belts of the Droning Maud Land (East Antarctica) (Jacobs *et al.*, 2008; Thomas *et al.*, 1994; Rediel *et al.*, 2013).

Remnants of these orogenic events are recorded within the Mozambique belt (Bingen *et al.*, 2009), establishing rocks with high anisotropy (Figure 40).

Although some general consensus exist regarding the Karoo grabens and rift basins having exploited the anisotropic properties of the pre-existing structures and orogenic belts (Verniers *et al.*, 1989; Watkeys, 1998; Catuneanu, 2005), there is currently no direct way of quantifying the influence of the paleo tectonic structures of the basement on the emplacement of the Karoo volcanic episodes, and its contribution to breakup of Gondwana.

Our objective is to study published geochronological data on the basement (see chapter 6) to identify domains of similar geochronological properties, and major shear zones and structural markers across the plates.

2.2 Studying the implication of the volcanic episodes in the Mozambique Channel in the context of the Pamela project.

The PAMELA project has a focus on the western part of the Indian Ocean, a complex domain associated with the movement of Madagascar, Antarctica and the South American continent plates from Africa. These plates drifted away during the Mesozoic breakup of the Gondwana, following three well-identified corridors discussed earlier. Each of these corridors are bordered by two strike-slip zones. The strike-slip zones separating the different corridors, and are zones of intraplaque deformation (transpression, transtension, and leaky fractures zones in purely oceanic domain). These margins were subjected to different volcanic episodes that strongly impacted the substratum and the sediments along the margin (Flores, 1975; Bristow, 1980).

The question of the ages and impact of volcanic episodes in the channel are not adequately unknown, and therefore currently lingering, despite their crucial implication on constraining the evolution of Gondwana.

Currently, at least four main volcanic intervals are recognized (Figure 41);

i. The Karoo flood basalts (179-183Ma Lower Jurassic).

ii. The Lower Cretaceous period with several distinct events: Movene Basalts (145Ma; Klausen, 2009), lupata rhyolites (166±10Ma Flores, 1964) and the Bumbani complex (142-143 Ma Klausen, 2009), including Chiloas province, (Bailey and Kearns, 2011) and kimberlites.

iii. Upper Cretaceous period, corresponding to the traps (basalt and rhyolites) of Madagascar (Turonian,

Ketchum and Barrett, 2004; Rocco *et al.,* 2013) and the Kimberlites of South Africa ().

iv. Tertiary events, with particular attention to an event at 40 Ma in Madagascar and also and above all the upgrading of Madagascar to the Upper Miocene (Andrianaivo and Ramasiarinoro, 2010; Rocco *et al.,* 2013). The Miocene period witnessed major volcanic event, which impacted large areas of Madagascar and Comoros.

Unraveling these different magmatic episodes allows us to beter constrain the geodynamic evolution of the events along the Africa-Madagascar-Antarctica margin, describing the crustal nature of the substratum, and major kinematic phases recorded. Indeed, the volcanic phases seem to manifest with different modalities following the established segmentation and perhaps the type of crust present. For example, the Turonian impacted Madagascar by setting up Trapps, and South Africa by setting up Kimberlites. The Mozambique Channel is therefore an ideal but complex site for studying holistically the impact of major kinematic and volcanic events on passive margin.

In Antarctica and Australia, the magmatism occurred around 182 Ma in the Dronning Maud Lands (Antarctica) and in Tasman (Australia) (Elliot, 1992; Duccan, 1997; Burges et al., 2014), and approximately 138Ma for the Explora Wedge (Mutterlose and Wise, 1990; Jokat *et al.,* 2003)

2.2(a) Challenging interpretations

This study is confronted by a number of challenging interpretations that should be linked to new seismic refraction and reflection data.

These interpretations include:

- MORB interpretation of Lebombo basalts (west of the Limpopo Basin) according to the Melluso *et al.* (2008).
- The interpretation of SDR's in the coastal plain of Limpopo, as proposed by Klausen *et al.,* (2009).
- The age of the youngest formation of the Lebombo complex: Movene basalts / Bumbani complex (dated 142-143 Ma Hatsie et al., 2013).
- The structural interpretation of the Limpopo Basin in the context of Gondwana's breakup.

2.2(b) Objectives

1. The primary objectives of PAMELA in this work is to firslyt provide a robust geodynamic framework through a compilation of the kinematic models, and to provide clear definition of the problems and implications and consequences (near and far) of each of the proposed solutions or hypotheses;
2. Secondly, evaluate current knowledge and work completed on the volcanism, to understand what remains to be achieved;
3. Thirdly, provide global context on the magmatic episodes, in order to understand its importance on the evolution of the margin. In order to achieve this objective, an upgrade of the current knowledge on the magmatic (age, nature, condition of implementation) is needed.
4. Fourthly, to understand the influence of kinematic movements on magmatism, margin architecture, and subsidence history.

Answers to the above objectives requires comprehensive new geochemical and isotopic dating, which is currently underway within the Pamela project.

Conclusions from the age dating are important to firmly validate or otherwise the hypothesis of the origin of the Karoo magmatism. The work on the new dating is currently underway.

CHAPTER 3: METHOLOGY

3.0 METHOLOGY

Producing a as much as possible holistic and coherent reconstruction of the India Ocean demands a multifaceted approach (Aslanian et al., 2009; Moulin et al., 2010; Aslanian & Moulin, 2012) by 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 the adjoining plates, in a global view, and to produce a model that is consistent and respect current data interpretations and field observations.

We first carried out a comprehensive examination of a number of large, but not complete published kinematic reconstruction models of the Indian Ocean, (more than 30 since 1977) to compare them on the same scale using PLACA and PALCA4D software (Matias et al., 2005), looking at their consequences on the continental passive margins and predictions on the nature and origin of the Mozambique and Madagascar aseismic ridges. These models were subsequently grouped into broad families.

We then undertook a compressive study of the basement of the plates: locking at the architecture and geochronological composition of their constituent Cratons and crustal block and delineating important structural markers in order to accurately juxtapose them to each other to obtain a more coherent initial fit. Indeed, Gondwana formed during the Pan-African Orogeny from 720 to 550Ma (Jacobs et al., 2003; Guiraud et al., 2005), consisting of Archean and Paleoproterozoic Cratonic cores, surrounding accreted progressively younger terrains of Mesoproterozoic and Neoproterozoic age (Jacobs et al., 2003; Dewaele, 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 marginal and rifts basins is very critical to unraveling the initial geometry of Gondwana and its disintegration.

A compilation of onshore and offshore geological and geophysical data in the Indian Ocean that could be accessed was therefore carried out, to understand the work that has already been done, 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 the Karoo event along the east African margin, and within the African plate were examined, and compared to Karoo events in Madagascar, Antarctica, and Australia to examine the different lithologic sequences that were deposited from the Late Carboniferous to Recent, and to also understand the evolution history of these basins.

A full-fit reconstruction needs to take into account the morphology and the nature of the passive margins as well as the main structural oceanic features produced by the break-up and the 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 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 better help constrain the initial fit. The plotting of the maps presented here was achieved with the help of Arcgis 10.2, PLACA (Matias et al., 2005) and Generic Mapping Tool (GMT) (Wessel and Smith 1998).

In our reconstruction and figures, we use the actual shape of the coastlines, where we assumed an unthinned substratum. Gaps and overlaps, which may appeared, must be explained by intraplate deformation that may have occurred after the breakup and that has deformed the shape of the coastlines since the break-up, and/or the presence of continental material offshore the coasts. If no evidences of such material or deformation are observed, the reconstruction must be modified (Moulin et al., 2010; Aslanian & Moulin, 2012). Therefore, in a given reconstruction, an overlap must be 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 a same way, a gap must be either explained by the existence of continental block off shore and/or by the existence of a range on the back 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).

It is important to note that this fit represents only the shape of Gondwana at the time of the fit and does not take into account the deformations that occurred before that time as the model of Reeves et al., (2016) try to do.

Reeves et al., (2016) assume, by analogy with actual passive margins, that the pieces of Precambrian crust that still exist in their full thickness, are separated by belts of about 250km of extended crust; assuming a thinning factor ß between 2 and 4, they proposed an assemblage of these Precambrian block at 182.7 Ma with a separation of about twice the typical crustal thickness (i.e. about 80 km, but +/- 20 km). The model of Reeves et al., (2016) presents therefore a tentative of reconstruction of the Gondwana, 20Ma before the break-up (and our reconstruction).

Whilst this attempt is a good first approximation which needs as these authors wrote: « More works need to be done to quantify [their] assumption » (the actual knowledge on the morphology of actual margins all over the world presents a very different view of Passive margin, with very different morphologies), it seems to us more sensitive to separate the pre-beak-up evolution in two steps, as we get more and more geophysical data and evidences on the margins and offshore. Having a good reconstruction at the break-up time will give us a good base to go back and test Reeves et al. hypothesis.

Finally, all our findings and interpretations from the different data sources were combined to propose a new pre-break-up fit of Gondwana. In May 2016, new wide-angle data were acquired on the Limpopo margin and Natal valley (Moulin & Aslanian, 2016; Moulin & Evain, 2016) in order to test the assumptions taken in our model.

To constrain the early motion of East Gondwana (Antarctica, Madagascar, India, Sri Lanka and Australia) and to build a model of the evolution of the Indian Ocean, indubitable magnetic anomalies of Leinweber and Jokat (2012) in the Mozambique Basin system was integrated, and of Davie *et al.* (2016) in the Somali Basin, leaving the weakly defined and higly questuionable ones, together with published seafloor fracture (e.g. Davie *et al.*, 2016) published in the ocean (Figure 42 and 43). Their fracture data was compared and supplemented by our own data in the Indian Ocean. The seafloor fabric and the magnetic anomalies within the Mozambique Basin, Somali Basin were visually matched using the Placa software. This method has been applied previously (e.g. Sahabi, 1993; Eagles and Konig, 2010; Konig and Jokat, 2010, Leinweber and Jokat, 2012; Davies *et al.*, 2016). These data were used to reconstruct East Gondwana movement relative to Africa from magnetic anomaly M25n to M0r. The geometry and architecture of Gondwana for the time M25n (157 Ma), M22n (147.815 Ma), M15n (135.76 Ma), M10 (130

Ma), M5n (126.12 Ma), M0r (120.8 Ma), C34 (98Ma), C28 (64Ma) and C18 (40Ma), were achieved through the visually matching conjugate magnetic anomalies and fracture zones within the Indian Ocean. (See the total poles describing the movements in table 1-7).

We tried to keep a single East Gondwana configuration, and visually match the magnetic anomalies and fracture zones in the Somali and Mozambique basins until we could no longer match the data in both basins maintaining a single East Gondwana Unit. Thereafter we allowed the Madagascar-India-Sri Lanka circuit to move independently of Antarctica-Australia. This occurred around M15n as was earlier suggested by Davies *et al.*, (2016). The subsequent motions were constrained using data from their individual basins.

CHAPTER 4: COMPILATION OF INDIAN OCEAN EVENT AND KAROO BASINS LITHOSTRATIGRAPHY

4.0 COMPILATION OF INDIAN OCEAN EVENT AND KAROO BASINS LITHOSTRATIGRAPHY.

4.1 Indian Ocean major tectonic event compilation

All the studies here were based on bibliographic data (scientific articles, brochures and papers).

4.1(a) West Somali Basin

This basin together with the Mozambique Basin constitute one of the oldest basins of the Indian Ocean (Figure 44). It opened during southward drift of Madagascar until anomaly M0 (120 Ma; Ségoufin and Patriat, 1980; Davis *et al.*, 2016), following the breakup of Gondwana.

Mesozoic magnetic anomalies in the Somali Basin were published by Ségoufin and Patriat, 1980; Parsons *et al.*, 1981; Masson *et al.*, 1982; Rabinowitz *et al.*, 1983; Davies *et al.*, 2016).

Ségoufin and Patriat (1980), using 3 north-south ship tracks interpreted an extinct ridge at approximately 7°S, M21n (148Ma, Tithonian), as the oldest magnetic anomaly in the basin, and the youngest anomaly M0 (119Ma, Aptian).

Masson *et al.* (1982) and Parsons *et al.* (1981), identified magnetic anomaly M22 (149 Ma, Tithonian), and the youngest anomaly M2 (123Ma Barremian).

Rabinowitz *et al.* (1983) reversed many of Segoufin and Patriat (1980) identifications through the analysis of one published ship track and 5 new ship tracks collected between 1980 and 1981. They identified the young end of anomalies M25n (157 Ma) through M9n (128.62 Ma) about an extinct ridge ranging from 5°S to 10°S. The hypothesis proposed by Rabinowitz *et al.* (1983) that Madagascar ceased its drift from Africa at M10 (129Ma), and implies an overlap of the Antarctic plate on Madagascar during its southward drift.

Cochran (1988) proposed an alternative magnetic interpretation. He interpreted anomalies M22n (147.18Ma) through M0r (120.6Ma) along an extinct ridge running from 4°S to 7°S. Eagles and König (2008) used the ship tracks from Rabinowitz *et al.* (1983), and reinterpreted anomalies M25n (153.43Ma) to M10n (128.93 Ma) about an extinct ridge from 5°S to 10°S.

More recently, Davis *et al.* (2016), recently, compiled all of the previously published ship track magnetic data as well as 2 previously unpublished ship tracks in the Somali Basin. Their interpreted extinct spreading ridge is similar in geometry and location to the ridge proposed by Segoufin and Patriat (1980). They identified M24Bn (152.43Ma) as the oldest magnetic anomaly in the Somali Basin.

4.1(b) North Somali Basin

The basin is bounded to the south by the Western Somalia basin, west by the Somali margin, and east by the Chain ridge (Figure 44). The age of the North Somali Basin remains undetermined. Currently, no magnetic anomaly has been identified in the basin (Sahabi, 1993).

Cochran (1988) suggested the basin to be underlain by Mesozoic crust created during the initial movement of India and Madagascar to the south, along with the basin of Western Somalia and the Mozambique basin. He suggested a large part of the basin located at the east of the Chain Ridge (see figure 46) subducted during the separation between India and Madagascar in the Upper Cretaceous, replaced by the basin of East Somalia and the Arabian basin. However, DSDP-234 (Fisher, Bunce *et al.*, 1974), located west of the southern tip of the Chain Ridge, shows the oldest sediments reached are of lower Oligocene (30 Ma).

4.1(c) Mozambique Basin

The Mozambique Basin is one of the first oceanic basins of the Indian Ocean, formed as a consequence of the breakup of Gondwana. The basin is bounded to the west by the Mozambique Ridge, east by Madagascar and the Madagascar ridge, north by the African plate, and occupies the central and southern parts of the coastal plain of Mozambique, extending onto the continental shelf and slope (Figure 45).

Here, the age of the oldest magnetic anomaly that can be associated with oceanic crust in the basin is debated. Segoufin (1978) and Simpson *et al.* (1979) first published Mesozoic magnetic anomalies sequence in the basin. They interpreted anomaly M22 (152 Ma, Kimmeridjian-Tithonian boundary) as the oldest Mesozoic magnetic anomaly in the basin. König and Jokat (2010) extended the identifications up to M26n close to 22°S 37 in the Zambezi Basin based on the magnetic survey of the MoBaMaSis project (Mozambique Basin Marine Seismic Survey). Leinweber *et al.*, (2012) repicked the magnetic anomalies of Konig and Jokat (2010), combining the MoBaMaSis data, with data from the AISTEK II cruise, and old ship data from the NGDC database, to extend the anomalies from weakly, defined M26 (157.3) to M41. Their data implies oceanization occurred earlier in the basin than previous thought. A recent reconstruction by Davis *et al.* (2016) for the Antarctica-Africa corridor based on the Leinweber and Jokat identifications in the Mozambique Basin, excludes magnetic anomalies older than M25, which have not been are presently observed on the conjugate margin. Hence, debate exists as to whether the old magnetic series (Magnetic anomalies older than M25) are magnetic field intensity variation, that result of magma underplating.

The general direction of fracture zones in the basin is NNE-SSW.

4.1(d) Riiser Larson Basin

This basin represents the Antarctica conjugate of the Mozambique Basin, which were opened during the initial breakup of Gondwana. The basin is bounded to the east by the Gunnerus Ridge, which is a north-south striking feature, extending from the coast at around 33.5°E, possible underlain by continental crust (Roeser *et al.*, 1996; Leinweber and Jokat, 2011). It is bounded to the West by the Astrid Ridge (Figure 45). The Astrid Ridge extends between 9°E and 17°E from 65°S south to the continental margin (Leinweber and Jokat, 2011). The ridge is separated into two parts, flanking the Astrid Fracture Zone (AFZ). The southern part strikes in about North-South direction up to 67°S, and the northern part is elongated in SW-NE direction following the AFZ trend. The crustal fabric as well as the geological evolution of the ridge currently remains speculative (Leinweber and Jokat, 2011).

Bergh [1977, 1987] identified magnetic anomaly sequence from anomaly M0 to anomaly M9 in the basin. Roeser *et al.* [1996] extended the identifications to M24 (152Ma). Jokat *et al.*, (2003) corroborated the picks of Roeser *et al.* [1996] with their clear pattern of the magnetic M-series up to M24 (152Ma). Konig and Jokat (2010) extended the picks to M25 (157Ma).

The general direction of fracture zones in the basin is NNE-SSW.

4.1(e) Natal Basin

The Natal Valley is bordered to the east by the Mozambique Ridge, west by Southeastern Africa. The Valley is divided into a southern and a northern part. The transition between the two parts located around 29° S after Leinweber and Jokat (2011). The southern Natal Valley was opened during the drift of the Falkland-Patagonia from Africa shortly before the M10 anomaly (Hauterivian Goodlad *et al.* 1982).

Goodlad *et al.* (1982) identified NW-SE Mesozoic magnetic anomalies sequences in the South Natal Valley. The oldest anomaly is the M10 anomaly (130 Ma, Hauterivian) and the youngest M0 (119 Ma, Aptian). The continent-ocean-boundary (COB) in the Natal Valley was proposed to coincide with the South Tugela Ridge [Martin *et al.*, 1981; Goodlad *et al.*, 1982].
However, conflicting interpretations exist on the nature of the crust underlying the Northern Natal Valley (Scrutton, 1976; Cox, 1992; Watts, 2001; Leinweber and Jokat, 2012]. The North Natal Valley (NNV) stretches between longitude 33-36E and Latitude 25-28S. Marks and Tikku (2001) and Tikku *et al.* (2002) identified anomaly M10 and M4 in the valley.

Leinweber and Jokat, (2011) proposed a complicated pattern of anomalies in the North Natal Valley with mainly SW-NE trends, with magnetic wavelengths similar to the Mozambique Coastal Plains. They identified no continent-ocean-boundary between the two basins based on both the free-air gravity and the magnetic field data. Lepretre *et al.* (2017), Verrier *et al.* (2017) and Moulin *et al.* (Submitted) present seismic refractions evidence in favor of the North Natal Valley underlain by continental crust.

4.1(f) Mascarene Basin

The Mascarene basin was opened during the separation of India and Madagascar, shortly before the anomaly 34 (before 83 Ma). The accretion in the basin stopped shortly after the anomaly 27 (62 Ma Dyment, 1991). The basin is bounded to the north by the Seychelles plateau, south by the Madagascar ridge, and East by the Mascarene and Saya de Malha plateaus (Figure 46).

Schlich and Fondeur (1974); Schlich (1982); Dyment (1991) have identified magnetic anomalies in the Mascarene basin. The oldest recognized anomaly is anomaly 34 (83 Ma), the youngest magnetic anomaly is anomaly 27 (62 Ma). Hence, the extinct NW-SE oriented ridge axis of the Mascarene basin operated in an era shortly before the anomaly 34 (before 83 Ma) and a period shortly after the anomaly 27 (after 62 Ma) (Schlich, 1982; Sahabi, 1993).

DSDP-239 (Simpson *et al.*, 1974a) drilled in the basin (2l°S, 51°E) reached the sediments overlying the basaltic basement. The sediments were dated Campanian (about 80 Ma), consistent with the magnetic anomaly identification.

4.1(g) Crozet Basin

The Crozet basin is bounded by the south western Indian ridge and the Conrad Ridge (Mounts Ob and Lena) to the north, the northern part of the Kerguelen plateau to the south, and the South Indian ridge to the east. This basin is considered conjugate to the eastern part of the Central Indian basin.

Magnetic anomalies were recognized in this basin by (McKenzie and Sclater 1971; Patriat *et al.*, 1985; Patriat 1985; Royer and Sandwell 1989). The oldest magnetic anomaly identified is anomaly 34 (Patriat *et al.*, 1985), situated to the north of the Conrad ridge in the western part of this basin. The youngest magnetic anomaly identified is anomaly 20.

Hence, the crust of the Crozet basin may have been created between anomalies 34 and 20 (Patriat *et al.*, 1985; Sahabi, 1993).

4.1(h) West Australian Abyssal Plain

The temporal and spatial evolution of the West Australian abyssal plains is crucial for accurately constraining the extent and kinematic history of Greater India and other continental blocks that rifted from the West Australian margin (Powells *et al.*, 1988; Sahabi, 1993; Gibbons et al., 2013). However, the reconstruction between these two plates is difficult since much of the oceanic crust formed between Greater India and Northwestern Australia has been subsequently subducted beneath Southeast Asia (Gibbons *et al.*, 2013).

The basins adjacent to the western margin of Australia are the Argo, Cuvier, Gascogne and Perth basins (Figure 47 and 48). They opened during the initial separation between Greater India and Australia. The Argo basin opened at M25 anomaly [156 Ma; Veevers *et al.*, 1985 or M26 (158 Ma; Fullerton *et al.*, 1989)]. The Cuvier and Gascogne were opened at M10 (130 Ma) and accretion stopped at MO (119Ma). The Perth basin was opened at M9 anomaly (129 Ma), and accretion stopped at anomaly M0 (119 Ma).

4.1(i) Argo Basin

The Argo Abyssal Plain is situated at the northern tip of the West Australian margin, about 600 km across and 5.7 km deep (Gibbons et al., 2013). The oldest magnetic anomaly identified in this basin is anomaly M26 (158 Ma, Oxfordian according to Fullerton *et al.*, 1989), or anomaly M25 (156 Ma, upper Oxfordian, according to Veevers *et al.* 1985). The youngest is the anomaly M16 (142 Ma, Berriasian). The opening of the Argo basin would therefore have occurred before the time of the anomaly M26 or of the anomaly M25.

4.1(i) Gascogne/ Cuvier/ Perth

The detailed study of the magnetic anomalies in these three basins was carried out by (Larson 1975; Powell *et al.*, 1988; Johnson *et al.* 1980; Veevers *et al.* 1985; Powell *et al.*, 1988; Gibbons *et al.*, 2013), highlighting two NE-SW fossil accretions in the Gascogne and Cuvier basins and a single fossil accretion axis also oriented NE-SW in the Perth Abyssal Plain. The magnetic lineations in these three basins are oriented NE-SW. They are interrupted to the north by the Argo Basin and to the south by the Broken Ridge.

The Gascogne basin: extends off the Exmouth plateau at its east, and south by the Cuvier basin. The oldest anomaly identified is the basin is anomaly M10 (130 Ma, Hauterivian), and the youngest identified anomaly is the anomaly M0 (119 Ma, Aptian) (Larson, 1975; Powell *et al.*, 1988).

The Cuvier basin: is located between the Wallaby plateau to the south and the Exmouth plateau to the north.

Powell *et al.*, (1988) published Mesozoic magnetic anomalies in the basin. The oldest anomaly identified is the M10 anomaly (130 Ma, Hauterivian), in the basin. The youngest identified anomaly is the anomaly M0 (119 Ma, Aptian). Debate currently exists on the original extent of Greater India, whether the crust in the Cuvier Abyssal Plain formed following breakup between the northernmost part of greater India or a separate continental fragment (Gibbons et al., 2013).

The Perth Abyssal Plain is the only region of preserved seafloor that directly records the history of Early Cretaceous seafloor spreading between India and Australia (Walliams *et al.*, 2013). It is located between the western continental margin of Australia and the southern section of the Wharton Basin (Walliams *et al.*, 2013). Its southern limit is marked by Broken Ridge and the Diamantina Zone.

The spreading direction in the PAP is broadly WNW-ESE, evidence from the orientation of the Wallaby-Zenith Fracture Zone (WZFZ), together with the Naturaliste and Batavia Fracture Zones. This is consistent with the orientation of magnetic lineations of west Australian margin (Walliams *et al.*, 2013).

The Perth Abyssal Plain and Wharton Basin meet at a zone of bend fracture trend, observed in free-air gravity data, which recorded a major change in relative plate motion around 99Ma (Veevers, 2000) or 100–105Ma (Matthews *et al.*, 2012).

4.1(k) Wharton Basin

The basin is bounded on the north by the Java trench, on the south by the Broken Ridge, on the west by the Ninetyeast Ridge, and on the east by the Mesozoic basins in western Australia West (Figure 48). This basin operated between India and Australia from the time of the major reorganization of the Middle Cretaceous (before 83 Ma) to the time of the Anomaly 20 (about 43 Ma) (Sahabi, 1993). Magnetic anomalies were identified in this basin by Sclater and Fisher 1974).

The oldest magnetic anomaly identified in this Basin is anomaly 33 (76 Ma), the younger is the anomaly 21 (47 Ma, Liu *et al.*, 19831 or the anomaly 20 (43 Ma, Royer and Sandwell, 1989).

4.1(l) Enderby Basin/ Bay of Bengal

Magnetic anomaly identification in the Bay of Bengal and off the Enderby Basin are characterized by debates, as a result of spare data, and the masking and interference from thick Bengal Fan sediments (>5 km), and igneous structures such as the 85°E and 90°E ridges (Gaina *et al.*, 2007 and references). Three alternative models are proposed. A model in which the age of early ocean crust formed during breakup is largely Cretaceous Normal Superchron (CNS) (~ 118– 83.5 Ma) crust with little or no Mesozoic sequence (e.g. Royer and Coffin 1992; Jokat *et al.*, 2010). Two, a model suggesting that older Mesozoic crust (135 Ma Ramana *et al.*, 1994a; Ramana *et al.*, 2001; Desa *et al.*, 2006; Gaina *et al.*, 2007) does exist between the two basins, and that spreading was roughly contemporaneous with the well-documented M-sequence (M10–M0) off the Perth Abyssal Plain (Powell *et al.* 1988; Gaina *et al.*, 2007). One of the problems of this model is that onshore massive volcanism occurred approximately 18 Myr (India-Rajmahal Traps; Antarctica-Kerguelen Plateau), after the first formation of oceanic crust along the conjugate margins (Jokat *et al.*, 2010).

Gaina *et al.* (2007) proposed a third model. They agree that the oceanic crust off Eastern India was formed during the Cretaceous Normal Superchron (CNS), but identified M series back to M9o about an extinct spreading axis located in the East Enderby Basin. The M series accreted with the Elan Bank still connected to India. During the CNS, finally, the Elan Bank drifted also away from eastern India, leaving Late Cretaceous oce

4.2 Karoo Basins lithotectonic event compilation

Onshore and offshore geological and geophysical data in the Indian Ocean that could be accessed were compiled, to review the work that has already been done, and to identify the main challenges and possible incoherencies that exist. Geological information on basins in the Indian Ocean was gathered: the age predictions of the rifting, the first oceanic crust, and the oldest magnetic anomaly (Figure 49). The intraplate volcanism within the various plates from the Triassic to the present age were also recorded and a chart of these events produced.

The Karoo basins preserve the lithostratigraphy record from Late Carboniferous–Early Jurassic of the Karoo Supergroup deposited into intracratonic rift basins in Gondwana (Catuneanu, 2005) (Figure 50). The formation of these basins was controlled to some extent by the preexisting structures (Faure *et al.*, 1996). The Karoo Supergroup consists of the Upper Carboniferous Dwyka Group, the Permian Ecca Group, the Late PermianMiddle Triassic Beaufort Group and the Late Triassic-Early Jurassic Stormberg Group capped for some of them by the Karoo Stromberg volcanics in South Africa and Mozambique (Figure 51). A synchronous volcanism, with ultramafic lamprophyre (UML) dykes and linear outcrop pattern parallel to the proto-Pacific margin of Gondwana, occurred in Antarctica, in the Ferrar province (Riley *et al.,* 2003). This Karoo-Ferrar volcanism is associated with mass extinction (Pálfy andSmith, 2000) and one of the most profound environmental changes in the Mesozoic taking place during Pliensbachian–Toarcian (Early Jurassic), including the Toarcian Oceanic Anoxic Event (Ikeda and Hori, 2014).

In East Africa, the basins occupy a roughly southwest trending strip, extending from southeastern Kenya and northeastern Tanzania to Lake Nyasa and Lake Rukwa, from where they continue into Zambia, Malawi and Mozambique (Wopfner, 2002).

In South Africa, the Karoo Supergroup is best preserved in the Main Karoo basin (MKB), which covers more than half of South Africa. Subsidiary Karoo basins are preserved to the north of the MKB in the Lebombo, Soutpansberg, Kalahari, Springbok Flats and Ellisras basins (Faure *et al.*, 1996; Wopfner, 2002).

Here, we discuss the East Africa Karoo Basins. Guillocheau and Liget (2009), provides a comprehensive report on the Southern Africa Karoo Basins.

4.2(a) Mombasa Basin

The stratigraphy of the Karoo sediments in Mombasa Basin has been investigated by Rais-assa, (1988) and Hakel (1992). Although diagnostic fossils are rare (Hankel, 1992), they suppose that this thick sequence of predominantly arenaceous sediments of continental origin may have been deposited between Permian to Lower Jurassic (Figures 51 and 52). Rais-assa (1988) described the evolutionary history of the sediments, which he subdivided into three major phases: (a) the Lower Karoo sediment with the Maji ya Chumvi Formation as the latest sedimentary unit, (b) the Middle Karoo basin with a stratigraphic sequence, which terminates with the Matolani Formation, and (c) the Upper Karoo basin, which corresponds to the Mazeras Formation. In general due to lack of fossils, the ages assigned to the Karoo sediments in this basin have large a uncertainty.

4.2(b) Tanga Basin-Tanzania

The Tanga basin preserves Karoo-age succession termed Tanga Beds (Quennell *et al.*, 1956; Wopfner, 2002) that rests directly on metamorphic rocks of the Usambara complex. The beds, which are informally sub-divided into a lower, middle and an upper sequence (Quennell *et al.*, 1956), record no exposures of older Karoo units (Wopfner, 2002).

Hankel, (1987), Wopfner and Kaaya, (1991), Wopfner (2002) presented detailed studies of the Tanga Beds. The Lower division commences with basal cobble to boulder conglomerates, followed by coarse grained, current-bedded, feldspathic sandstones and green or red siltstone interbeds (Wopfner, 2002). The middle sequence rests unconformable on the lower division and consists largely of dark, carbonaceous siltstones and fine grained sandstone (Wopfner, 2002).

The upper division of the Tanga Beds consists of brown to white, thinly bedded and current bedded flaggy sandstones and green mudstones (Wopfner and Kaaya, 1991; Wopfner, 2002). The Beds are unconformably overlain by coarse grained and intensly current-bedded, fluviatile Kilulu Sandstone, whose age is undertermined (Wopfner, 2002). The Karoo succession is unconformably overlain by marine carbonates of Early to Middle Jurassic age (Wopfner, 1994; Wopfner, 2002; Hankel, 1987).

4.2(c) Selous Basin- Tanzania

The lithostratigraphy of the Karoo sediments in the Selous Basin has been carried out in great detail in (Hankel, 1987; Wopfner, 1994; Catuneanu, 2005; Guillocheau and Liget, 2009). The basin records no exposure of Carboniferous to Early Permian Karoo sequences (Wopfner, 1994). The succession begins with conglomerates and boulder beds of the Hatambulo Formation, which rests unconformably on Proterozoic metamorphics of the Uluguru Horst (Hankel, 1987; Wopfner, 1994). The Hatambulo Formation is overlain by the Rufiji Formation with a strong unconformity separating the two formations (Wopfner, 1994 and references herein). The overlying units are represented by braid-plain deposits Lohombero Formation and the Mahogo Formation (Hankel, 1987; Wopfner, 1994), which are topped by the Ladinian to the Early Norian red beds of the Luwegu Formation (Wopfner, 1994), The Karoo sediments are finally represented by the Mkuju Formation.

4.2(d) Ruhuhu Basin- Tanzania

The Ruhuhu Basin records a complete succession of the Karoo sediments (Wopfner, 1994). Here, the Karoo sediments termed Songea Group are exposed on the rift shoulder of the modern Nyasa Rift (Wopfner, 1994; Wopfner, 2002) consisting of about 3000m of Late Carboniferous to Early

Triassic, dominantly siliciclastic deposits (Wopfner 2002, and references herein). Wopfner (1994), Catuneanu (2005) presented a detailed stratigraphy of the Ruhuhu Basin. The PermoCarboniferous Lower succession is divided into four depositional sequences. The basal sequence is formed by the glacigene Idusi Formation, overlaid by the coal-bearing Mchuchuma Formation. The third sequence, the Mbuyura Formation, consists of coarse, feldspathic scarp sandstone at the base (Wopfner, (1994), which is overlaid by the Ruhuhu Formation, a thick succession of green, lacustrine mudstones and stromatolitic carbonates (Wopfner, 1994; Catuneanu, 2005). The sequence is topped by the Usili Formation that rests with an erosional disconformity on the preceeding Ruhuhu Formation (Wopfner, 1994).

The final depositional sequence is formed by the dominated Manda Beds, which are composed predominantly by sandstone (Wopfner, 1994; Catuneanu, 2005).

4.2(e) Metangula-Basin-Mozambique

The Metangula Basin is formed by large grabens system running NE-SW from Mozambique through to Tanzania to coastal Kenya (Verniers *et al.*, 1989; Catuneanu, 2005). Here, the Karoo supergroup was presented by Verniers *et al.* (1989). They divided it into three sequences. The upper consists of about 5 km of fluvial sediments of possible Beaufort up to Stormberg age infilling the grabens. The middle Karoo is of lower Beaufort age consists of approximately 600 m of red mudstones with a number of fossil reptile bone levels. The lower sequence deposited during the Permian is approximately 330m thick and mainly composed of sandstones and silts with some carbonaceous horizons.

4.2(f) Ruvuma Basin:

The existence of Karoo sediments in the Ruvuma basin is unclear. A layered sequence wedging out towards the west on the flank of the trough, truncated by overlying strata has been identified in industrial seismic profiles and has been compared with the Karoo deposits of Tanzania in the Selous and Mandawa basins (Wopfner, 1994; Catuneanu, 2005; Salman and Abudulla, 2005).

None of the above mentioned previous basins are overlained by volcanic sequence.

4.2(g) Mana-Pool/ Cabora Bassa - Basin-Zambia

Barber (1994), d'Engelbronner (1996), and Catuneanu (2005) have described the Karoo deposits in the Mana-Pool and Cabora Bassa. The Mama-Pool basin is separated from the Cabora Bassa basin by the metamorphic basement rocks of the Chewore Inliers (d'Engelbronner 1996). These two basins share comparable Karoo stratigraphy (d'Engelbronner, 1996; Catuneanu, 2005). At the base of the Karoo Supergroup is the Kondo Pools Formation, characterized by massive, coarse-grained pebbly sandstones, often interbedded with conglomerates (d'Engelbronner, 1996). The overlying Mkanga Formation is composed of poorly-sorted sandstones at its base and is up to 1000 m in thickness (d'Engelbronner, 1996). The Angwa Sandstone Formation overlay the Mkanga Formation comprising of basal massive Sandstone with fine grain alternations (d'Engelbronner, 1996). The overlying Pebbly Arkose Formation, varying in thickness from 850-2000 m, is characterized by medium- to very thickly-bedded, pebbly, subarkosic and arkosic arenites (d'Engelbronner, 1996). The Karoo deposit is finally overlain by the Forest Sandstone Formation which consists predominantly aeolian fine-grained sandstones (d'Engelbronner, 1996).

4.2(h) Mid-Zambezi-Basin-Zimbabwe

The Karoo Supergroup is deposited unconformably on basement in the Mid-Zambezi basin (Orpen *et al.*, 1989; Hiller and Shoko, 1996; Catuneanu, 2005). The basin displays typical alternating half-grabens (Hiller and Shoko, 1996) with a lobate southern margin and listric faults on the northwestern side (Hiller and Shoko, 1996). Here, the Karoo Supergroup is composed of the Late Carboniferous-Early Permian glaciogene Dwyka (Hiller and Shoko, 1996; Catuneanu, 2005). The Ecca age sandstones and coal of Lower Wankie Sandstone, the Coal Measure and Upper Wankie Sandstone (Hiller and Shoko, 1996; Hiller and Shoko, 1996; Orpen *et al.*, 1989). This is overlaid by the Madumabisa Formation, lower escarpment grit, middle ripple marked flagstone, upper fine red marly sandstone of Beaufort age (Hiller and Shoko, 1996).

The overlying pebbly Arkose Formation, varying in thickness from 850-2000m, is characterized by medium- to very thickly-bedded, pebbly, sub-arkosic and arkosic arenites (Hiller and Shoko, 1996). The overlying Forest Sandstone, is of desert facies sediments (Hiller and Shoko, 1996).

4.2(i) Lower Zambezi

Bond (1973) and Broderick (1981) studied the Karoo sediments in the Lower Zambezi Basin.
The Lower Karoo lithologies have not been adequately described in this basin, except in Mozambique where some deposits are reported (Broderick 1981). In Zimbabwe the Karoo sequence is correlated lithologically with Upper Karoo series. The oldest unit mapped contains late Triassic flora at its base, described to correlate with the Fine Red Marley Sandstone of the Mid-Zambezi, and are typical of the Stormberg Series in South African (Bond, 1973).

4.2(j) Ellisras-Basin-South Africa

The Ellisras basin preserves the Karoo sequence in faulted blocks and a half-grabens paralleling Limpopo mobile belt (Faure *et al.*, 1996 and references herein). The Lower Karoo Dwyka Sequence composes of the Waterkloof and Wellington Formations. The Waterkloof Formation consists of diamictite, mudstone and conglomerates, and Wellington Formation consists of mudrock and sandstone intercalations which become more common toward the base (Faure *et al.*, 1996; Catuneanu, 2005). The Ecca sequence overlies these lithologies and is divided into the Swartrant and Grootegeluk Formations. The Swartrant Formation overlies the Wellington Formation with an erosional contact and is composed of sandstone, grit, siltstone, carbonaceous mudrock and coal seams. The overlying Grootegeluk Formation is composed of carbonaceous mudstones with interbedded bright coal seams (Faure *et al.*, 1996), overlained by medium to light grey massive mudstones of the Eendragtpan Formation, which is the base of the Beaufort Group (Faure *et al.*, 1996; Catuneanu, 2005). The Beaufort Group is composed of the Greenwich Fm at the base, the Lisbon Fm, and the medium to fine sand deposits of the Clarens Fm at the top.

4.2(k) Morondava/Majunga - Madagascar

Karoo Supergroup in Madagascar has been presented in several studies (Hankel, 1993; Geiger *et al.*, 2004; Catuneanu, 2005; Guillocheau and Liget, 2009). Here, the Karoo sequence comprises the Sakoa group at the base, the unconformably overlying Sakamena group and the top lying Isalo Group in the Morondava and Majunga basins deposited in downfaulted rocks and overlain by post-Karoo Mesozoic strata (Catuneanu, 2005). The sedimentation started in the Late Carboniferous and ceased in the Early Jurassic (Hankel, 1993).

Records of interrupted continental sedimentation by marine ingressions from the Tethyan Ocean documented by the presence of brackish water horizons and shallow marine deposits from the Early Permian times onwards becoming dominant in the mid Jurassic (Geiger et al 2004, figure 54) has been reported in the two basins (Hankel, 1993). The Sedimentary infills are represented mainly by continental red-bed sedimentation.

4.3 Karoo Basins evolution – discussion covering the age of the first oceanic crust

The analogy of the Karoo event having resulted in the breakup of Gondwana is proposed by many workers of different research background (sedimentologist, paleontologist, geochemist etc..) working in different parts of the Karoo basins.

In general, the deposition of sediments in the Karoo basins in Eastern and Southern African was controlled mainly by tectonic and climatic regimes (Catuneanu, 2005). The plate experienced flexural deformation resulting from the subduction of the Panthalassa oceanic crust, and an extensional Tethyan rift regime propagating from the Tethyan margin along the East African margin (Catuneanu, 2005) (Figure 51).

The tectonic regime varied from predominantly flexural deformation in the south, in relation to processes of subduction, accretion and mountain building along the Panthalassan margin of Gondwana (establishing the remnant Cape Fold belt, and the retroarc foreland Main Karoo Basin) (Bordy and Catuneanu, 2001; Catuneanu, 2005) to extensional deformation in the north in relation to spreading processes along the Tethyan margin of Gondwana (Hankel, 1993; Catuneanu, 2005; Guillocheau and Liget, 2009). The constructional and extensional tectonic regimes, combined with climatic fluctuations on the African continent (Guillocheau and Liget, 2009) as the African plate moved from the South Pole to the North Pole, influenced the basin development and infill (Bordy and Catuneanu, 2001, 2005). The climatic conditions changed from cold to semi-arid during the Late Carboniferous to Early Permian, to warmer and eventually hot climatic conditions by the end of the Beaufort and Stromberg time establishing desert conditions in the Kalahari. These fluctuations left a mark across the stratigraphic record and therefore provide a trend linking the different sedimentary fill of the Karoo basins that formed under the different tectonic regimes (Catuneanu, 2005; Guillocheau and Liget, 2009).

Three stages of rifting were recognized literature (figure 52).

- *Late Carboniferous to Lower Triassic stage: it* marks the beginning of the rifting along the East African margin followed by a period of unconformity in the middle Triassic (Bordy and Catuneanu, 2002; Catuneanu, 2004). However, some workers prefer a much later start of the rifting, arguing that older rifting age proposals are not strongly constrain by geological data.
- *Upper Triassic to lower Jurassic stage:* this rifting event was interrupted in some basins by the Karoo volcanic event for, which some associate with later successful breakup of Gondwana.

- *Middle Jurassic to upper Jurassic stage*; these rifting event is observed in the Belo and continental red beds. The Belo Formation consists of conglomerates and continental sediments deposited on the weathered Karoo volcanics (Flores, 1964 and 1975, Salman and Abdula, 1995). This rifting event, according to our interpretations, which we discuss in chapter 5.2, marks the successful breakup of Gondwana in the Indian Ocean. The end of this rifting event is contemporaneous with the deposition of the rhyolites, which are observed in the Lupata formation (Flores, 1964, 1975, 1980), and most coherent with the oldest confidently dated magnetic anomaly in the Indian Ocean.

There are general incoherencies in the time period predicted for the breakup in the Somali and the Mozambique Basin, which are presented on figure 54 and 55. It is observed from this figure 55 that the predicted age for breakup in the Somali basin from the summary compilations starts from as early as Late Triassic to Oxfordian. However, the predictions for the oceanization also go back to the Toarcian with the deposition of Andafia beds (Figure 54) (Geiger *et al.*, 2004), this then leads to an overlap between oceanization and rifting between Toarcian and Callovian.

Similar observation is brought to bear on the compilation on the Mozambique and surrounding basins (Figure 55). The rifting started in the Late Triassic and ended in the Late Middle Jurassic. Oceanization is also argued to have started in the Middle Jurassic (e.g. Burke and Dewey, 1973; White and McKenzie, 1989; Duncan *et al.*, 1997; Watkeys, 1998, 2002; Eagles and Konig 2008; Klausen, 2009; Hastie et al., 2014; Gaina *et al.*, 2013; König and Jokat, 2010; Leinweber and Jokat, 2011, 2012), with the intrusion of the Karoo volcanims leading to overlap of possible rifting and oceanization at the same time between late-Early Jurassic and Middle Jurassic. This assumption is further challenge since after the intrusion of the Karoo volcanism, the basin experienced a long period of hiatus or non-deposition in the Middle Jurassic, and the volcanics were exposed to subaerial or surficial conditions. The conglomerates and continental red beds of the Belo Formation were later deposited across the volcanics. If oceanization had occurred during the Karoo volcanic intrusion, then it becomes very difficult to explain the long period of subaerial exposure of the volcanics and the depositions of the conglomerates and continental sedimentary units on the volcanics.

One might expect marine sedimentary units at this time, but the marine sedimentary units are observed rather in the Upper Jurassic, a strong indication that the breakup in the area occurred in a later event follow the Karoo volcanic event. Moreover, no older age magnetic anomaly of the age of Karoo has yet being observed in the Mozambique basin, rather most of the ages older than M25 is observed to fall within the COT. The confidently dated oldest anomaly in the Riiser Larson Sea and in the Mozambique Basin is anomaly M25, recognized about 200km from the shoreline of the two conjugates basins.

Thus the age range for the rifting in Gondwana may be longer than previously proposed (e.g. Geiger *et al.*, 2004 proposed the rifts in the Somali Basin to have terminated in the Lower Jurrasic). However, the rift may have continued well into the upper Middle Jurrasic initiating continental breakup oldest oceanic crust in the Indian Ocean around anomaly M25 (157Ma).

CHAPITER 5: CONSTRAINTS FROM NEW OFFSHORE GEOLOGICAL AND GEOPHYISCAL DATA

5.0 CONSTRAINTS FROM NEW OFFSHORE GEOLOGICAL AND GEOPHYISCAL DATA

The Indian Ocean is remarkably characterized by numerous offshore geological structures (aseismic ridges and plateau), whose topographic expressions vary widely from linear features to more rounded plateaus. Although there have been several attempt to describe the nature of offshore structures like Agulhas Plateau, Kerguelen Plateau, Beira High, Natal Valley, Maurice Ewing Bank, Mozambique and Madagascar ridges etc. in the Indian Ocean, intense debates are still ongoing as to whether they existed during the amalgamation of Gondwana or were formed sometime after its fragmentation. Some of these plateaus like the Seychelles are known to compose of Precambrian crustal rocks (Jaeger et al., 1989; Knight et al., 2003) and are therefore considered as continental fragments, a relic of India as it continued its drift from Madagascar. Ashwal et al. (2017) reported of archaean zircons in Miocene oceanic hotspot rocks beneath Mauritius. They therefore proposed the Mauritius continental plate spaced between Madagascar and India Maurice before breakup between the two plates.

Several others like the NinetyEast, ChagosLaccadive, and Mascarene Plateau, are however believed to be the traces of hotspot activity. Fortunately, there has been recent efforts to acquire new geological and geophysical data to try to answer these questions. We examine current published data on these key structures to ascertain their origin, as these structures have strong implications on the reconstruction of the Gondwana's initial geometry, and are therefore crucial to investigate.

5.1(a) Maurice Ewing Bank

The Maurice Ewing Bank (MEB) represents the easternmost portion of the Falkland plateau. DSDP Hole 330 was bottomed in 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± 66Ma (Lorenzo and Mutter, 1988) correlative with the similar age granite of the Cape sequence of Southern Africa (Thomas et al., 1997; Jacobs and Thomas, 2004; Riedel et al., 2013).

Reconstruction of the MEB to the southern of the Tugela ridge is presumed to be the effective northern limit of the Natal Valley beyond which the Maurice Ewing Bank 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 the Tugela ridge to mark the COB in the

Natal Valley. The newly acquired seismic data of PAMELA-MOZ3-5 project tend to support their assertion (Lepretre et al., 2017; Moulin et al., submitted). Consequently, models moving the Falkland Plateau-MEB beyond the ridge into the NNV become problematic, except there has been significant crustal extension in the Valley.

5.1(b) Agulhas Plateau

The Agulhas Plateau is about 750km long in a north-south direction and 400km wide. The plateau covers an area of 300 000 km2 and rises about 2.5 km above the surrounding ocean floor (Barrett, 1977 and Gohl et al., 2001).

Previous studies analyzed dredged rock samples of Precambrian ages to the southern part of the ridge (Allen and Tucholke, 1981). The problem with this plateau as identified in a number of reconstruction models is that the plate tectonic reconstruction of the South Atlantic and Southwest Indian Ocean region from the Early Cretaceous at isochron M0 until the Late Cretaceous at isochron 34 does not allow for the Agulhas Plateau to have existed before the breakup of the Falkland Plateau from southern Africa, and the Mozambique Plateau due to its size. Therefore it tends to mean that the time of formation its formation postdates the time of initial rifting. Forming after the Falkland Plateau had slid toward the southwest along the Agulhas Fracture Zone in the Cretaceous.

Martin (1987), however suggested that if the crust of the present southern Agulhas Plateau existed before the Gondwana breakup, it was probably situated adjacent to the Mozambique Ridge and south of the Falkland Plateau at around 130Ma but at approximately 80-100 Ma, the Bouvet hotspot was centered beneath to its northern tip and may have provided a source of volcanism for the northern part.

Seismic data interpretations (notably Gohl et al., 2001; Barrett, 2001) on the Plateau identify a basement layer having a seismic velocity of 4.8 4 km/s overlying the main crustal layer with velocity 6.72 km/s, therefore interpretating an oceanic nature. He notes the plateau resembles certain volcanic features like the Chagos Laccadive and Hawaiian Ridges in the Indian and Pacific Oceans, which are thickened relative to normal oceanic crust, due over thickened volcanic piles. The Agulhas Plateau is interpreted to be of oceanic origin. The Agulhas Plateau was apparently formed during or after the separation of the Falkland Plateau from southern Africa. In our model volcanic origin is suggested for the Agulhas Plateau, South Mozambique Ridge and Maud Rise (MR) possibly at a triple junction around anomaly MO as has been previous suggested by (Konig and Jokat, 2010, Leinweber and Jokat, 2012). The main eruption phase possibly lasting to about 90 Ma after which the South Mozambique Ridge, the Maud Rise and Agulhas Plateau may have detached by continued seafloor spreading (Parsiegla et al., 2008). Such considerations then eliminate the possible overlap with the Falkland plateau.

5.1(c) Mozambique and Madagascar Ridges

The Madagascar Ridge is 400 km across, extending southwards from the Madagascar continent for 1300 km with water depth between 2 and 3 km over most of the plateau. Dredge sample of continental material in the northern part of the ridge led to interpretation of continental origin by Schlich et al., (1974). The South Madagascar Ridge was however interpreted oceanic in origin by Goslin et al. (1981) with the depth to Moho of 14km having possibly being formed between 90Ma-70Ma (Schlich et al., 1974 and Goslin et al., 1981).

The nature and origin of the Mozambique ridge 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). According to Leinweber and Jokat (2011), the Mozambique ridge is comprise of several bathymetric plateaus rising up to 3,500m from the ocean floor, separating two Mesozoic ocean basins that formed at different spreading regimes (The Early Cretaceous South Natal Basin, and the Upper Jurassic Mozambique Basin). It has broad elevated topography on its southern half, and falls steeply into the Mozambique basin on its east.

Its origin (whether continental or oceanic) has large impact on the reconstruction of the Indian Ocean. An oceanic origin implies it was formed sometime after breakup of Gondwana, and allows an overlap by other continental plates, continental origin on the other hand means its existence precedes the breakup and cannot simply be overlapped by other continental 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 andMoulin, 2012). Raillard and Mougenot (1990) and Ben Avraham et al. (1995) partitioned the ridge into a northern oceanic and a southern continental crust with Moho depth of about 22km. A continental origin was however favored by Tucholke et al. (1981) and Hartnady et al. (1992), when dredged samples of Archean fragments (Tucholke et al., 1981; Raillard, 1990; Mougenot et al., 1991; Ben-Avraham et al., 1995) were retrieved along the eastern and southern Mozambique Ridge composing of anorthosites, gneiss and metagabbros (Martin et al. 1981).

Indications of a possible oceanic origin for the ridge came from first direct samples during DSDP leg 25 hole 249, where MORB-like rocks were retrieved (Thompson et al., 1982; Ben-Avram et al., 2005), and magnetic anomalies identification by Leinweber and Jokat, (2011).

Unfortunately, radiometric dating was not undertaken. Recently, Gohl et al. (2011) provided seismic refraction evidence in support of the southern part of the Southern Mozambique ridge having an oceanic origin, possibly formed due excessive volcanism at a triple junction. Furthermore, within the PAMELA project, the recent expedition in the Mozambique Basin during MOZ3-5 (Lepretre et al., 2017; Moulin et al., submitted) found the North Mozambique Ridge (NMR) to consist mainly of an alignment of sediments over a thinned continental crust.

Consequently, on the basis of the seismic refraction evidence by Gohl et al. (2011) and Lepretre et al., (2017), we believe to represent thick oceanic basement the South Mozambique ridge, and thin continental basement overlain by sedimentary produced by currents on the north of the ridge.

5.1(d) Natal Valley

The North Natal Valley (NNV) stretches between longitude 33-36E and Latitude 25-28S. Marks and Tikku (2001) and Tikku et al. (2002) identified anomaly M10 and M4 in the valley and considering a continental origin for the Mozambique ridge proposed a rotation pole between M11 and M2 to avoid an overlap with Antarctica. Leinweber and Jokat, (2011) identified SW-NE trending magnetic anomalies within the NNV, and suggested it to be floored by thickened oceanic crust with the Continent Ocean Transitional (COT) lying close to the Lebombo range.

The newly acquired seismic data of PAMELA-MOZ3-5 project present seismic evidence in favor of the contitnental crust in the North Natal Valley (Lepretre et al., 2017; Moulin et al., submitted).

5.1(e) Limpopo Basin

The stratigraphic sequence of the Limpopo Basin sedimentary section consists of a wedge that thickens eastward from the exposed pre-Cambrian basement into the Indian Ocean. The geologic history of the area is dominated by rifting that preceded and accompanied continental breakup. Some of these rifts were later reactivated in the Lower and Upper Cretaceous during the opening of the South Atlantic in the Lower Cretaceous (Salman and Abdula, 1995).

The inland Lebombo monocline is flank to the west the Mozambique Basin; it dips regularly eastward at 10 to 20 degrees (Klausen, 2009) under the sedimentary units. Field works conducted by several researchers including Flores (1964, 1970) have shown several vents and dykes that occur in the Limpopo Basin. Flores notes that the successive inclination of the pipes and proposed that when related to the time of intrusion and effusion of the magma, indicates that the eastern coastal plain was being tilted as the effusion occured.

Cox (1992) and Klausen (2009) identified SDR’s in the Limpopo Basin. Cox (1992), related the SDR’s development to a plume event, which resulted in subaerial spreading in the basin. Cox (1992) proposed two stages of breakup for Gondwana. The first stage involves Early Jurassic reactivation of old shear zones in the Limpopo Basin and in Maputo, and a northeastwards movement of Antarctic creating a zone of thinned continental crust or mixed oceanic and continental crust. The Karoo volcanism and plume and the SDRs of Lebombo and western part of Explora Wedge (Hinz, 1981) were emplaced at this stage. The second stage took place 10-30 Ma later (in the Middle Jurassic), when the Antarctica-Madagascar-India-Australia-Sri Lanka circuit moved southwards creating the oldest known oceanic crust in Indian Ocean. He proposed a ‘new concepts of volcanic margin development’ to argue the point about the break-up and Karoo volcanism, and the apparent paradox of 30 Ma gap with the first magnetic anomaly in the Indian Ocean. The interpretations of oceanic crust in the Limpopo Basin, were based on geochemical and gravity data. Their argument contradicts Salman and Flores and coworkers, who had proposed the Limpopo and Natal basins to be underlain by continental crust as based on their seismic reflection and geological studies. The pre-Karoo volcanic unit were interpreted here as syn-rift Carboniferous – Triassic Karoo sediments (Flores 1964, 1975; Salman and Abdula, 1995).

By contrast, Storey (1995), believed that the Karoo plume only played an indirect role in break-up of Gondwana by thermally weakening the lithosphere and inducing local rifting but not resulting in breakup between Africa and Antarctica.

Domingues et al. (2016), subsequently, interpreted a possible transitional crust, with crustal thickness between 20 and 30 km beneath the basin. Rather than a continuous sheet of Karoo effusive spreading in the Limpopo Basin into the current known oceanic crust, Flores (1970, 1975), suggested possible existence of a series of parallel, trending fractures issuing ever younger magma from W to E.

Our analysis of Total seismic data in the basin (Chapter 5.2), and recent seismic refractions results of PAMELA-MOZ3-5 project (Lepretre et al., 2017; Verrier et al., 2017; Moulin et al., Submitted) suggests the basin maybe underlained by continental crust.

5.1(f) Beira High and Zambeze Depression

The Beira High is approximately 280 km long and 100 km wide (Mahanjane, 2012), elongated in northeast-southwest direction, and subparallel to the Zambeze coastline. It is located in water depth between 1000 to 2500 m and buried by Mesozoic and Cenozoic sedimentary sequences (Mahanjane, 2012; Muller et al., 2016). The question of the true origin of the Beira High has been controversial for a long time (see chapter 2.1(f)). Leinweber et al. (2012) interpreted older magnetic series M28-33 on the crust, and proposed oceanic origin.

Following these authors, recent kinematic models (Leinweber and Jokat, 2012; Gaina et al., 2013, 2015) have regarded its nature to be oceanic. However, Muller et al. (2016) presented new seismic refraction and gravity data on the High in support of continental crust, and the Zambezi depression underlain by possible thinned/stretched intruded continental crust. Following this new data, all kinematic models that overlap the Antarctic plate on the High consequently become unsupported.

5.1(g) The Kerguelen plateau

The Kerguelen plateau is divided into three parts (northern, central and southern parts). The plateau has been the subject of several geophysical surveys and Ocean Drilling Program drill sites (ODP Legs 119, 120, 183, and 188). Deep-crustal seismic refraction data (Charvis et al.1995), reveal up to 24 km thick crust comprising a lower crust of 15 km thickness with velocities increasing from 6.4 to 7.4 across the northern part. The basalts recovered from the ODP sites provide oldest ages of 119 Ma for the southern Kerguelen Plateau (Duncan, 2002), whilst some sample from Leg 119 have geochemical signatures which suggest a subcontinental lithosphere origin. Seismic data from Alibert (1991) show lower crustal velocities of less than 6.9 above a 23 km deep Moho (Gregoire et al. 1998). According to Gaina et al. (2007), this may suggest that a ridge jump could have isolated continental fragments from the India margin and attached them to the East Antarctic plate. ODP Legs 119 (sites 738–746), 120 (sites 747–751) and 183 (sites 1135–1142) were drilled with the object of further investigating the Kerguelen Pleateau. The recovery of core material including garnet-biotite gneiss on Elan Bank indicated a continental origin. The similarities in (Nb/La) and (Th/Nb) between lavas from the

Elan Bank, Wallaby Plateau (Western Australia), and the Naturaliste Plateau, and the their relative depletion in Nb, was considered by (Gaina et al., 2007 and Watson et al., 2016) to indicate of their derivation from fragments of continental crust. According to Watson et al. (2016), the Kerguelen plume volcanism, prior to the formation of the south Kerguelen Plateau (110–119 Ma) was widespread beneath East Gondwana, starting with relatively low-supply interspersed continental volcanism and increasing dramatically during the formation of the South Kerguelen Plateau. And that during its peak production (119–100 Ma), the plume extruded voluminous volcanic sequences to form the Southern and Central Kerguelen Plateau (105-95Ma Frey et al. 2000). The plateau largely overlaps the Broken Ridge at ages before C34 in it central part. Recent seismic and geochemical studies on the Broken Ridge (Coffin et al., 1986; Ducan, 2002), interprets oceanic origin for the ridge, emplaced around 100-90Ma, contemporaneous with formation of the central Kerguelen Plateau.

5.1(h) Observations from the Tethys Ocean

The quest to resolve the age of the first oceanic crust in the Indian Ocean motivated us to search and compare major tectono-thermal events within the Indian Ocean to its surrounding oceans (e.g. the Tethys and Central Atlantic Oceans) which existed before Gondwana breakup. Various ages have been propended, spanning from the middle Jurassic (183Ma; Duncan et al., 1997; Klausen, 2009),), to the Early Cretaceous for the first oceanic crust. The basis for these age propositions come from different sources: sedimentary, gravity and magnetic data and volcanic intrusion analysis. A consensus among workers has not yet being achieved and the debates are still ongoing.

The Tethys Ocean due to its existence before the breakup and drifting of Gondwana and its proximity to Gondwana, recorded the major tectono-magmatic events (Figure 56 and 57). The Tethys Ocean was created after collision of Gondwana with Laurasia in the Permian, and it lasted until the Late Cretaceous. Between these periods, the Paleo-Tethys Ocean was formed, subducted and obducted beneath Eurasia and thereafter the Meso-Tethys opened. In the same manner, the Meso-Tethys closed and the Neo-Tethys opened. The subduction, collision and obduction of these oceanic crust and a number of continental blocks that rifted from Greater India and the Northwestern Australian margin (Gondwana), with the Eurasian plate, eventually resulted in the formation of the Alpine-Himalayan Orogenic Belt and the Eastern Oman Ophiolite Belt of eastern Arabia (Gnos et al., 1997). The Western Ophiolites belts of Pakistan also records major tectono-magmatic events that has remarkable correlation with major events in the Indian Ocean from the Cretaceous. The eastern Ophiolites belt of Oman has being extensively studied in details by many workers. This ophiolitic belt is characterized by ocean floor fragments created during the Late Jurassic (157Ma Gnos et al., 1997) to the Late Cretaceous C34 (Kazmin, 1989; Gnos et al., 1997) between East Africa-Arabian and Greater India. This ocean is referred to as the Neo-Tethys Ocean (Gnos et al., 1997). The Ocean was affected by renew tectono-thermal activity between 130-120Ma (Kazmin, 1989 and Gnos et al., 1997). This was a period of large scale plate reorganization, which is reflected in the Indian Ocean (Separation of the Elan Bank from Antarctic, the formation of the Curvier, Perth and Gascogne basins on the Northwestern Australian margin) and in the South Atlantic.. The late Jurassic age recorded by these ophiolites marks the opening of the Neo-Tethys Ocean between Africa-Arabian and Greater India. The event correlates with M25 (Veevers et al.,(1988) or M26 (Fullerton et al., 1989) magnetic anomaly identification in Northwestern Australian Basin, and with the confidently dated oldest magnetic anomaly in the Mozambique and Somali basins (Rabinowitz et al., 1983, Leinweber and Jokat, 2012). The collision of the Central Afghanistan block onto Eurasia leading to the closure of the Meso-Tethys Ocean is noted by (Gnos et al., 1997) to have occurred around this time in the late Jurassic. The Central Atlantic Ocean was also impacted at age M25 (Labails et al., 2010). Labails et al. (2010), observed a major change in direction of plate propagation from NW-SE to WNW-ESE at anomaly M25.

Figure 57 summarizes the major events recorded in the Tethys Ocean (in the ophiolitic belt of Eastern Oman and Western Pakistan). Notice the good correlation of the tectonic events with the Indian Ocean. The M41 event was not recorded in any of the surrounding oceans.

5.2 Seismic Data

Exploration activity began in Mozambique (Figure 58) at the beginning of the twentieth century. The first wells, 100m deep, were drilled in the Inhambane province near reported surface seepages (Salman and Abdulla, 1995), with some of the wells producing water with oil film. The next period of activity occurred between 1927 and 1937, during which period seven wells were drilled on the Inhaminga uplift in the central part of Mozambique. These wells terminated at approximately 2,000 m. Exploration activities stalled in the early 1940’s, but increased again from 1948 an when several contracts was signed by foreign companies such as were Gulf Oil. Exploration activity declined in the early 1970’s because of increasing political unrest and finally ended in 1973. After a hiatus of some eight years, exploration for hydrocarbons was reestablished in the early 1980’s, when Empresa Nacional de Hidrocarbonetos de Moçambique

(ENH), the national oil company of Mozambique was established to issue licenses and exploration rights for petroleum resource. The State Secretariat for Coal and Hydrocarbons (SECH) entered into agreements with Western Geophysical and Geophysical Company of Norway (GECO) in 1980, for the acquisition of seismic data over the whole of the continental shelf, with the aim of initiating modern exploration offshore Mozambique. These surveys were carried out during 1981/82, covering the offshore area of Mozambique to water depths of approximately 500 m. 12,800 line kms of seismic data covering the southern part of the Mozambique Basin from the South African border northwards to latitude 20º S, was acquired by Western Geophysical. It was based on 5 x 10 km grid. GECO, on the other hand, shot approximately 11,300 line kms in the area to the north of Western Geophysical survey. Their survey included the Zambezi Delta and the Rovuma Basin up to the Tanzanian border. Their basic grid was again mainly 5 x 10 km. Gravimetric and magnetic survey were recorded simultaneously with the seismic acquisition. The interpretation of these surveys provided a foundation for future explorations, and allowed the formulation of a licensing strategy by ENH. After several companies including Shell, Pan American Oil Co (Amoco), Japanese National Oil Company (JNOC), Esso, Leipzig VEB Geophysic and the ENH, have carried out a number of seismic surveys between 1980 and 1997. In 1998/99, Western Geophysical acquired additional 12,500 line kms of seismic data in two phases covering deepwater areas from the 1000m isobath to beyond the 2,000m isobath in the Mozambique Basin (ECL ENH, 2013). In addition to the seismic data, several wells have also been drilled in the Mozambique Basin. Since the early 1950s to the end of 1999 a total of 72 wells have been drilled. Of the total number, 49 were exploration wells, and 23 were drilled as appraisal wells (ECL ENH 2013). In our study, two types of data were applied to study the Limpopo and north Natal Basins; seismic reflection and well data. The reflection seismic database consists of an extensive set of offshore industrial 2D seismic reflection profiles (around 32 000 km) made available by TOTAL. These lines were shot between the 1980's and the 2000's. Six exploration wells were used to constrain our seismic interpretation in lithology, age and depositional environments. Sunray-1 was the principal well used, and its ages was correlated with Sunray-2, 3, 4, 7, and 12.

We undertook interpretation of these seismic data to delineate oceanic, continental, and transitional domains, and to identify any major fault structures and directions of fault propagation in the Mozambique Basin. In the Limpopo Basin, we also connected onshore and offshore lines to understand the extent of the previously described Landward Dipping Reflectors on the Limpopo margin (Hinz 1981; Cox, 1992):

• Seismic LINE- 09 was combined with lines B03-A B03-B, and B01-A in the Limpopo Basin (figure 58).

• Seismic LINE- 10 was similarly combined with onshore lines B02-A and B03-B (figure 58).

In addition, new seismic refraction and reflection data were acquired during the MOZ3-5 cruise in the Mozambique Channel (Lepretre et al., 2017; Verrier et al., 2017; Watremez et al., 2017; Moulin et al., submitted).

The analysis of the seismic profiles was based on Mitchum et al., (1977) seismic facies characterization (Onlap, toplap, downlap stratal truncations), to determine depositional sequences, and the progradational and retrogradational migration of the shoreline. Our principle objective was to try understand the structure of these basins, and complement the results with the refraction data to predict the nature of the crust underlying this area. Guillaume Baby and Jean Pierre Ponte (PhD students of University of Rennes 1) presented detail discussion on the postbreakup characterization of the seismic lines in the Mozambique basin.

5.2(a) Limpopo-Natal Basins stratigraphic interpretation

5.2(a)i Pre-Karoo Volcanic Sedimentary Unit

The sedimentary unit in the Limpopo basin has been previous interpreted as volcanic Landward Dipping Reflectors (LDRs) (Cox, 1992; Klausen, 2009). Onshore, Seaward Dipping Reflectors (SDRs) were also identified in the Lebombo and western part of Explora Wedge (Hinz 1981). On the onshore extension profiles, the so-called SDRs and LDRs are connected by strong deep corrugated reflectors (brown area, Figures 59-62). Overlapping them, we clearly identify a horizon with a high amplitude reflector (violet horizon on all figures). Although age-dating information is generally lacking on this horizon, Flores and Salman reports of Macia NW-1, Nhamura-1, Sunray-7 and Sunray-12 wells, which were drilled into this unit. The horizon was described as interbedded volcanic and sedimentary complexes. On the Natal Plateform, we can recognize strong deep corrugated reflectors (brown area figure 63), very similar to the corrugated reflectors of the Limpopo basin (Figure 59).

Several drills (Sunray-1, 2, 3, 4, 7, 12, Funhalouro-1, Palmeira-1, Macia-1x, Nhamura-1 –

Flores, 1964; Salman and Abdula, 1995) reached the volcanic violet horizon, which caps the brown reflectors. The seismic resolution of this unit is poor, due to poor penetration of seismic energy.

It generally displays high amplitude, low-frequency reflectors. Previous work have interpreted this unit as ‘’ Karoo volcanics’’, whilst varied ages were reported for the volcanics (From K/Ar- 285.6±14.3 to 116.8±8 Flores, 1964) in these wells, indicating they may not have been emplaced in one single event. The interpretations of oceanic crust in the Limpopo basin were first based on geochemical and gravity data. Anyway, the Nd/Sr analysis shows clearly that the basalts sampled in the drill have neither a composition of MORB nor SDRs (Sidonie Révillon, pers. Comm. 2017).

5.2(a)ii Red Beds and Maputo Formations (Late Jurassic – Early Cretaceous)

Above these deep reflectors, two sequences can be identified: a green horizon present only in selected places and a yellow layer that we were able to identify and connect all around the Limpopo Natal area.

The green horizon (Figures 59 to 62) shows evidences of growth strata indicating syn-rift deposition, characterized by a wedge geometry thickening basinward, with sub-parallel reflectors onlapping the basement. The spatial distribution of extensional faults within the unit are oriented NW-SE. In the Natal Valley, the NW-SE extension affecting the unit, is attributed by Baby (2017) to the initial deformation of the Agulhas-Falkland Fracture Zone (AFFZ). It has been penetrated in wells drilled in the Palmeira and Chedinguele Grabens. They were encountered in Sunray-1, 3, 7, Palmeira-1. The horizon represents non-marine continental sandstones and sandy clay layer thickening in the Chedinguele grabens (Figure 63). The age of this horizon is poorly constrained.

We successfully identify the yellow sedimentary layer, which passes over the zone of crustal uplift that flanks the Limpopo margin and continues on the oceanic crust (Figure 60 to 62), giving an age younger than the one of the oceanic crust, i.e. of about 150-145Ma. This layer was successfully continued along the Natal plateform to the drill Sunray1 and corresponds to the Maputo formation (Figures 62 and 63). This formation presents progradational sequence infilling onshore rifts and faults structures, and offshore flexuration and early drifting basins.

They are characterized by subparallel sequences, onlapping the hangingwall dip slope offshore, and progradational infilling of remnant rift depression onshore. The Main depocentres of this horizon is located in the inner margin rift depressions onshore, and on the newly formed oceanic crust.

We interpret the (brown area) deep reflectors in the Limpopo Basin and North Natal Valley, as pre-drift continental sedimentary or volcano-sedimentary layer, deposited into intracratonic sag basins. The age is possibly Late Carboniferous- Late Triassic? With superimposed possibly Triassic faulting (Guillocheau and Liget, 2009). If the Volcanic layer belongs to Karoo event, there is a sedimentary gap of more than 30Ma between this event and the first sedimentary deposit.

The uplifted zone along the Limpopo Margin is characterized by flexuration and uplift of the basement leading to margin morphology change and strong erosion of the Maputo sediments. This erosional unconformity was observed in the Qoteniqua Basin and dated Turonian by Baby (2017). Here, the geometry of the first onlap termination is parallel suggesting that significant relief was present before marine flooding.

In the Natal Valley, the Maputo Formation represents the initial flooding of the shelf in the Early Cretaceous. In the Limpopo Basin, it represents the first major flooding of the shelf after the formation of first oceanic crust offshore. The top of this sequence is represented by the Late Aptian Unconformity (Salman and Abdulla, 1995).

Line-09 (Figure 59) records evidence of volcanic activity Early Cretaceous intruding the Maputo Fm. These volcanic units are composed of high amplitude reflectors with typically poor reflection coherency beneath the unit. In Mozambique basin, columnar rhyolites (166±10Ma, Flores, 1964), were recorded in the Lupata Gorge.

5.2(a)iii Lower Domo Shales (Aptian-Albian)

The Blue horizon (The Lower Domo Shales) represents progressive progradational infilling of the relief of the Margin created during the Turonian uplift (Baby, 2017). It is a post-rift sedimentary wedge onlapping toward the continent.

The Lower Domo Shales represents major Mid Cretaceous transgression of the shelf comprising continuous high-amplitude, parallel reflectors that locally exhibit low-angle clinoforms that downlap onto the Maputo Formation, dominated by marine mudstones with some bands of arkosic sandstones (Salman and Abdula, 1995). The thickness of the formation increases considerably within the Chedenguele Graben on line LINE-03 (Figure 62). The Maputo Formation and the Lower Domo Shales are the marine equivalent of the continental Sena Formation. The Sena Formation occupies the central and northern parts of the Mozambique Basin (Salman and Abdulla, 1995), widely developed in the Lower Zambezi graben. It is a continental rock sequence of variegated fluvial and alluvial formations: arkose sandstones, conglomerates and argillites enriched with coaly detritus.

5.2(a) iv Domo Sandstone (Albian-Cenomanian)

Unconformably overlying the Lower Domo Shales is the Domo Sandstone, a sand-prone interval best developed in the central portion of profile LINE-03 (Figure 62). It is a reflective sequence high amplitude, continuous reflectors containing late Cenomanian-Mid Turonian fauna (Salman and Abdula, 1995).

5.2(a)v Upper Domo Shale (Late Turonian –Santonian)

Overlying the Lower Domo Shales (Green) represents Upper Domo Shale, which is composed of overall regressive dark grey, marine shales and clays interbedded with thin glauconitic sandstone and siltstone beds (Salman and Abdula, 1995). The formation is typically 600-650 m thick coarsening upwards with aggradational continuous, high amplitude reflectors (Salman and Abdula, 1995). The top of this sequence marks a regionally intra-Senonian Unconformity. Sunray-2 and 4 terminated in basic intrusives within the Upper Domo Shale.

5.2(a)x Insights from unconformaties

The Pre-breakup rift history within the Limpopo and Natal Valley may have been supressed by later volcanic intrusions and regional uplift. The volcanic episodes continued well into the Early Cretaceous, which may have contributed in retarding the initial thermal after breakup and creation of first ocean crust around Tithonian (anomaly M22) offshore Limpopo Basin and around Berriasian (M10) in the South Natal Valley. Thermal subsidence therefore may have occurred in the Early Cretaceous when the influence of the volcanism has wane down. The unconformities identified on seismic lines in the Limpopo and Natal Basins correlate with major global tectonic events. The period of major volcanic event overlying the pre-drift sedimentary unit may correspond to the Lower-Middle Jurassic Karoo volcanism that affected major areas of Southern Africa and Antarctica (Dronning Maud Lands; Alhmannryggen, Staumsvola, Vestfjella, Kickpatrick, and Dufek massifs, and the Ferrar Province). In Australia with the intrusion of the Tasman dolerite and Queensland volcanics. As noticed above, if this volcanic layer belongs to Karoo event, there is a sedimentary gap of more than 30Ma between this event and the first sedimentary deposit (Upper Jurassic Red Beds). Another hypothesis would be a Kimmeridgian-Tithonian age associated to the Gondwana break-up. Such younger ages are found in the Bumbeni-Movene basalts (figure 63).

The Neocomian unconformity (the unconformity between the Maputo Formation and the Red beds) is interpreted to marks a period of uplift and formation of oceanic offshore Limpopo Basin. The Early Cretaceous extension and volcanism in the north Natal corresponding with a period of crustal separation and formation of oceanic crust in south Natal Basin, and the opening of the south Natal valley and Austral segment of the South Atlantic at M10 (Moulin et al., 2010). This period also includes the intrusions of alkaline magmas and kimberlites and the intrusion of the Chilwa

Province (133-113Ma). The East-West Explora Wedge was also initiated along the Droning Maud land at this stage. This period saw large scale plate reorganization in the Indian Ocean, leading to the formation of Curvier, Perth and Gascogne basins on the northwestern Australian margin (Veevers et al., 1988).

The Aptian unconformity (unconformity the Lower Domo Shale and Maputo Formation) corresponding to the stop of Madagascar's drift from East Africa. Madagascar and Greater India stopped their southward drift from Africa at M0. The accretion in the Curvier, Perth and Gascogne basins also stop at M0. Intra-Senonian Unconformity (the unconformity between the Domo Sand and Upper Domo Shale) correspond to C34 a period that saw the breakup India and Madagascar, and Australia and Antarctica. The rise of the supposed Marion plume (centered in south/eastern Madagascar) at 90 Ma, the initiation of spreading in the Mascarene Basin at 84 Ma, and the rise of the Deccan plume.

The Early Eocene Unconformity between correspond to a stop of accretion in the Mascarene basin at C27, and a ridge jump to initiate seafloor spreading between Seychelles and India at C27 with the arrival of the Reunion hotspot initiating the Deccan Traps of India (66Ma) and the basalts on the Seychelles microcontinent.

The Late Eocene Unconformity correspond to the period of India collision with Eurasia.

We present a structural map of the basin in Figure 66.

1- The Limpopo and North Natal Valley share similar crustal thickness (> 30-35 km), surrounded by a thick sequence that we assume sedimentary or sedimentary volcano (neither MORB nor SDRs). On top this sequence, is a volcanic sequence, which cou be Karroo Thitonian. There is a problem of subsidence difference between North Natal and Limpopo. The subsidence between the two basins is not uniform.

2- In North Natal, several phases of volcanism are observed on the seismic section. In South Natal, onset of crustal thinning and subsidence is unknown (Goodlad et al., 1982)

3- The oceanic crust begins south of Natal at M10.

4. Along the eastern edge of Natal-Limpopo: on the continental shelf area (Lepretre et al., 2017; Moulin et al., Submitted), there is significant thinning and presence of sediments due to activity of current on the slope. This is the northern part of what was called the Mozambique Ridge. The southern part is probably a volcanic plateau from the operation of a triple point between the two segments Natal – Zambezi.

5- The oceanic crust, to the east, is divided by fracture zones (we see differences in crustal thicknesses on the seismic).

CHAPTER 6: ONSHORE BASEMENT GEOLOGY

6.0 ONSHORE BASEMENT GEOLOGY

6.1 Onshore 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 plate share similar age and orogenic history with three neighboring plates (Africa, India and Australia) (Boger, 2011) (figure 67). We have compiled from (Kelly et al., 2002; Gosh et al., 2004; Boger, 2011; Riedel et al., 2013) the geology of Antarctica (figure 67) and from (Daly, 1989: Dewaele, 2003; Guiraud et al., 2005; Jacob et al., 2006; Rhaka et al., 2013) the geology of Africa (figure 68) to delineate important structures markers that trends between the two plates. Based on geochronological properties and similar orogenic history preserved in Antarctica compared to three of its neighboring plates; Zone 1 (blue rectangle figures 68) is related to the Kaapvaal Craton of Southern Africa, Zone 2 (red rectangle figures 69) is related to the Eastern Ghats Craton of Eastern India, and Zone 3 (yellow rectangle figure 70) is associated with the Australian plate, with a number of Cratons and continental blocks trending between the two plates (for eg the Gawler nucleus of Australia forms an extension of the Mason Craton in Antarctica (Borg and DePaolo, 1991; Boger, 2011).

6.1(a) Antarctica-Africa Structure of the Archean-Proterozoic basin (Zone 1)

The Kaapvaal shield consists of Archean and Paleoproterozoic core surrounded by accreted younger terrains of Mesoproterozoic Namaqua-Natal and Neoproterozoic Pan-Africa orogenic belts (Jacob et al., 2003; Dewaele, 2003; Guiraud et al., 2005; Rhaka et al., 2013; Riedel et al., 2013). The shield bears strong 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 was placed south of the Mozambique belt in Gondwana (Thomas et al., 1994; Jacobs et al., 2008; Riedel et al., 2013) (Figure 68).

The Namaqua-Natal belt 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; Reidel et al., 2013), with the main collisional event taking place at 1135Ma (Rhaka et al., 2013; Riedel et al., 2013). It represents one of the very few areas of Mesoproterozoic crust in Gondwana that lacks significant overprint of Pan-African orogenic event (Jacobs et al., 2003; Riedel et al., 2013). In Antarctica, the Mesoproterozoic orogenic and magmatic activity that forms the Maud Belt has been dated between 1171±25 to 1045±9Ma (Jacobs et al., 1998, 2003), near contemporaneous with the Namaqua-Natal event. Suggesting these two events can be linked into one single Namaquan-Natal-Maud orogenic belt (Jacob et al., 2008). This provides some important evidence in support of the Antarctic plate situating south of Mozambique at least during the 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 (Bingen et al., 2009), granting some 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 into Somalia ang 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 that still remains is, what was the geometry of these structures and has far did they extend within Gondwana? In the many reconstructions (e.g. Jacobs and Thomas, 2004; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweber and Jokat, 2012; Torsvik et al., 2012; Seton et al., 2012; Gaina et al., 2013; Reeves et al., 2015; Nguyen et al., 2016), Antarctica (Grunneghona) is allowed to overlap directly the Limpopo basin some 300km from the Mozambique shoreline. This assumption, implying an underlained oceanic crust in the Limpopo basin, has serious implications on the temporal and spatial evolution of the Mozambique margin.

Aeromagnetic studies of dyke swarms of the Lebombo Mountains have been associated with rifting of Gondwana (Watkeys, 2002; Reeves 2000; Reeves and Mahanjane, 2013; Reeves et al., 2016). The dykes of 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), postulate the dyke swarms and probably other Lebombo-parallel dykes, to be related to an initial east-west separation of Africa and Antarctica in the earliest fracturing of the plates within the mosaic of Gondwana.

Duncan et al. (1997), Klausen (2009), Hastie et al. (2014) postulate the basin to be floored by Karoo volcanics younging seaward from the Lembobo range (Watskey, 2002; Klausen, 2009), and the Karoo volcanic event having resulted in the breakup of Gondwana. However, the evolution proposed by Klausen (2009) implies a main NW-SE movement of the Antartica plate with respect to Africa which is not coherent with the N-S Limpopo margin orientation.

Moreover, the geochemical analysis of the Karoo rocks (Melluso et al., 2008) onshore in the Limpopo Basin shows a composition that is not of MORB composition, nor SDRs, as is inferred by all model, that overlap Africa and Antarctica.

Bristow (1980) observed that the Karoo basalts show both enriched and depleted mantle sources, and therefore predicted that these basalts have been sourced differently. He also observed that the rhyolites show high Sr and Ba components, with high enrichment in K and Na compositions. He therefore predicted that these rhyolites may have been sourced from the partial melting of previously underplated basaltic magma which may have contaminated the magma leading to the high Sr, K and Na contents. His work reinforces the different source origins of the Karoo magmas.

Flores (1964, 1975), on the hand observed that, instead of a continuous sheet of Karoo effusive underlying the basin, the basin maybe characterized by series of parallel trending fractures issuing ever younger magma. Domingues et al. (2016) applied seismic ambient noise tomography in the basin, and observed low crustal velocities along with a thinning of the crust. They interpreted a possible transitional crust, with crustal thickness between 20 and 30 km. They agreed with Flores, noting that the emplacement mechanism suggested by him may have led to some magnetic signatures.

Lastly, preliminary results from recent seismic refraction and reflection data acquisition in the basin (Lepretre et al., 2017; Verrier et al., 2017;) suggest that he Natal Basin may not be underlain

by oceanic crust but 35km thick crust probably of continental nature, this will be in contrast to the reconstruction models that require overlap of Antarctica over the basin.

6.1(b) Antarctica-India Structure of the Archean-Proterozoic basin (Zone 2)

The geology of the India basement was compiled from (Ghosh, 2004; Dasgupta et al., 2013; Rajaprian et al., 2014; Tucker et al., 2014; www.portal.gsi.gov.in/portal 11/07/2016) (figure 69). Rocks of the Archean Napier complex of East Antarctica links well into part of the Eastern Ghats Shield during the Mesoproterozoic times (Kelly et al., 2002; Gosh et al., 2004) together forming the “Indo-Napier segment’’ described by (Gosh et al., 2004). The segment collided with East Antarctic basement in Mesoproterozoic during the amalgamation of Rodinia

Supercontinent (Fitzsimons, 2000) producing the crustal fragments constituting the Rayner Complex. The Rayner Complex links well into from Enderby Land into the Eastern Ghats Granulite Belt in India (See new model, figure 80).

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 Gosh et al., 2004) permits a close juxtaposition of India to Antarctica in Gondwana. The data is further strengthen 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 links well into the two plates (Kelly et al., 2002; Gosh et al., 2004; Biswal and Sinha, 2004).

6.1(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 70). The Mawson Shield continues from Antarctica into Australia (Borg and DePaolo, 1991; Boger, 2011). In Australia, it is called the Gawler block. This block is geochemically and geochronological correlative with the rocks exposed in the Miller and Shackleton Ranges of the Mawson Shield (Boger, 2011).

The Beardmore Block of Antarctica also bears similar geochemical and geochronogical properties with the Curnamona Block in Australia. According to Boger (2011), the Curnamona-Beadmore blocks collided with the Mawson Shield during the Paleoproterozoic Nimrod–Kimban orogenesis (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 conjugate in Antarctica bearing similar geochemical and age characteristics. The above geological data combine with the recorded geophysical data [Magnetic anomaly from anomaly C34 to C0 (Cande and Mutter, 1982)], gravity and bathymetry data between the plates makes their reconstruction the least complicated among all Gondwanan plates.

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

The geology map of Madagascar was compiled from the studies of (Besairie and Collignon, 1972; Courrier and Lafont, 1987; Nesen et al., 1988: de Wit et al., 2000; Rasoamalala et al., 2013; Tucker et al., 2014: Rekha et al., 2014) (figure 71).

The Archean sequence in Madagascar is represented by Archean rocks outcropping in Antongil and Fenoarivo, flanked by mostly juvenile granite–greenstone belts of Neoarchean and Paleoproterozoic rocks of Antananarivo (2.5–2.45 Ga) (Tucker et al., 2014).

The Eastern Archean rocks in Madagascar share similar geochemical properties with the Western Dharwar Craton in India, permitting trace of important geological structures into the two plates and their juxtaposition to each other.

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

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

The Dharwar Craton collided with the Tanzania Craton during the East African orogeny, leading to the closure of an ocean that previously separated them (Collins and 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 may suggest that the Dharwar Craton may have extended into Bur Acaba and beyond. According to de Wit (2003), Madagascar’s east coast originated together with rocks of the Indian Craton and were 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) (Bingen et al., 2009 and Tucker et al., 2014) share similar geochemical properties. 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 early Ediacaran time (0.65– 0.63 Ga Tucker et al., 2014).

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

The Falkland Islands is currently agreed to by a number of workers (Greenway 1972: Martin et al., 1981: Martin and Hartnady, 1986: Thomas et al., 1997 Curtis and 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 the Southern Africa shows a remarkable correlation in both structural style and timing of deformation with the Cape Fold Belt (Lock, 1978; Martin et al., 1981; Marshall, 1994; Curtis and 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., 1981 and Marshall, 1994). The oldest rocks making up the Falkland plateau are Mesoproterozoic basement (980-1100 Ma, Jacobs et al., 1998) (figure 72) 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 a single 1.1Ga Mesoprotorozoic terrain which was accreted to the Kaapval-Grunehogna Craton during the Mesoprotorozoic times. The terrain was partially rejuvenated during the Pan-African 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.

6.1(g) Sri Lanka Proterozoic basement geology

The geology of Sri Lanka was described after Kelley et al. (2002), and Tucker et al. (2014) (figure 73). The basement consists of the Paleoproterozoic Highland, Wanni and Vijayan complexes, which were overprinted by a PanAfrican orogenic event. The Vijayan complex share similar geochronological properties with Lutzow Hölm Complex of Antarctica (Kelley et al., 2002; Bigen et al., 2009; Tucker et al., 2014; Rekha et al., 2014), and therefore allows for reconstruction of Sri Lanka to the Lutzow Hölm area (See our new model, figure 80). In the model, the prominent 600km 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 (Bingen et al., 2009).

6.2 Initial fit reconstruction (misfit between geological constraints and previous models)

Figures 74 present analysis and comparism of nine (Sahabi, 1993; Leinweber and Jokat, 2012; Torsvik et al., 2012; Seton et al., 2012; Gaina et al., 2013; Reeves et al., 2015; Nguyen et al., 2016; Klimbe and Franke, 2016; Davis et al., 2016) recent palinspatic models of the Indian Ocean. These models were selected to examine and compare them, to understand their geological basis. We highlight their differences and consequences on the evolution of the margins, on the basis of current geochemical and geochronological data from the basement geology, and important structural markers that we have been able to delineate on the various plates.

These models vary widely in their initial fit positions mostly occasioned by the use of different data sources and varied data interpretations. In Konig and Jokat (2006), Leinweber and Jokat (2012), Gaina et al. (2013), the model is based mainly on interpretation of magnetic profiles, and assumption of oceanic nature for the the aseismic ridges (Beira High, the North Natal Valley (NNV), North Mozambique (NMR) and Madagascar Ridges, and Limpopo Basin), and hence producing a tight fit between Africa and Africa They argue the Karoo volcanism to have resulted in the final breakup of Gondwana and end with a tight reconstruction of Gondwana. This assumption leads to the Antarctic plate overlaping across the Limpopo basin. However, the Karoo lavas according to Riley et al. (2005), 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 (Riley et al., 2005), 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 onshore rock analysis in the Limpopo Basin shows a composition, which does neither fit a MORB composition nor SDRs, as supposed by all model which overlap Africa and Antarctica.

A stepwise study of major structures in the Indian Ocean was conducted understand their origin and evolution through time, so as to appropriately and adequately describe them in full-fit reconstruction in (Smith and Hallem, 1970: Sahabi, 1993). These models involve the incorporation of different data sets, from different data sources; seismic reflection and refraction, sedimentary deposits, volcanisms, magnetic anomalies, gravity and bathymetry data, etc., and ended with a less tight reconstruction.

There is however another category of models involving the reconstruction of two to three plates. The major problem with many of such models is the less regard for the impact of the models on surrrounding plates and data constrain from other sources (Aslanian & Moulin, 2012). An example is the model by Klimbe and Franke (2016), who prefer a more southward position of Madagascar, linking the Lurio belt to the Ranotsara shear zone.

We examine the impact of their model in figure 79. The model leads to huge gap of about 1000km between Antarctica and the Zambezi coastal plain taken into cognizance current information and observations on the surruonding plates.The position of Madagascar in Klimke & Franke 2016 presents huge differences in direction, position and conjugate passive margins compared to (Sahabi, 1993; Leinweber and Jokat, 2012; Gaina et al., 2013; Reeves et al., 2015: Davis et al., 2016).

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., 2015: Davis et al., 2016), which seem to correlate Majunga and Lamu Basins (Leinweber and Jokat, 2012; Reeves et al., 2015; Davis et al., 2016), and the Morondava and Tanga-Mombasa basin (Sahabi, 1993). However, the position seems to us too tight, without any room for the continental passive margin, which are offshore the coastlines, resulting in overlap of the continental crusts.

6.2(a) Antarctica-India

Figure 75 compares the reconstruction of India-Antarctica in (Sahabi, 1993; Leinweber and Jokat, 2012; Torsvik et al., 2012; Seton et al., 2012; Gaina et al., 2013; Reeves et al., 2015; Nguyen et al., 2016). Notice Seton et al. (2012), Gaina et al. (2013), Reeves et al. (2015), Nguyen et al. (2016) misfit Archean rocks of the Napier complex and the Eastern Ghat Craton, and the conjugate Gondwanaan rifts basins. 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. Sahabi (1993), Leinweber et al. (2012) and Reeves et al. (2015), presents a perfect alignment of Archean rocks of the Napier complex and the Ghat Craton (see also Ghosh et al., 2004). A good alignment of Gondwanan rifts basins and the Mesoproterozoic rocks is also achieve in these three models. Notice however, the ~450km overlap of the India plate on the Antarctica plate in Leinweber et al. (2012) and Reeves et al. (2015).

6.2(b) India-Madagascar

Figure 76 compares the fit between Madagascar and India in the same models. In Leinweber and Jokat (2012) and Reeves et al. (2015), 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.

Sahabi (1993) fits the Moyar shear zone to the Batsimisaraka shear. Seton et al. (2012), Gaina et al. (2013) and Nguyen et al. (2016), on the other hand results in about ~140km gap between India and Madagascar and inaccurately fits Mesoproterozoic rocks to Archean rocks between the two plates. 6.3(c) Consequences on Beira high, North Natal Valley and Falkland plateau In figures 77, we examine the consequences of these models on the Beira High continental block, the Limpopo basin, the North Natal valley, and the Falkland plateau (Greenway 1972; Martin et al., 1982; Martin and Hartnady, 1986; Thomas et al., 1997; Curtis and Hyam, 1998; Jacobs et al., 1998).

All models except Sahabi (1993), overlap the continental the Limpopo Basin the North Natal Valley, (Mahanjane, 2012; Mueller et al., 2016; Lepretre et al., 2017; Verrier et al., 2017), Seton et al. (2012), Leinweber et al. (2012), Torsvik et al. (2012), Gaina et al. (2013), Reeves et al. (2015) based on interpretation of some presumed magnetic anomalies on the Beira High and the North Natal Valley (Leinweber et al., 2013 and Leinweber and Jokat, 2011), which are infirm by the recent wide-angle seismic results.

Notice also that all the models, except Sahabi (1993), overlap the North Mozambique ridge, assuming oceanic origin, also described as thin continental crust (Lepretre et al., 2017;).

6.2(d) Falkland and Africa

Figure 78 presents a comparism of the fit between Falkland and Africa in Leinweber and Jokat (2012) and Konig and Jokat (2006) (orange), and Martin et al. (1982) and Martin and Hartnady (1986) (green).

Notice Konig and Jokat (2006) and Leinweber and Jokat (2012) (orange) models push the Maurice Ewing Bank beyond the limit of the continental boundary in (Lepretre et al., 2017), a boundary beyond which the Maurice Ewing Bank cannot be accommodated.

6.3 Geological correlation between continental results of the different plates.

6.3(a) Antarctica-Africa- Falkland fit

Our reconstruction of Antarctica to Africa (figure 79) was achieved on the basis of the geochronological and geochemical constraints of (Daly, 1989; Kelly et al., 2002; Dewaele, 2003; Gosh et al., 2004; Guiraud et al., 2005; Jacob et al., 2006; Boger, 2011; Riedel et al., 2013; Rhaka et al., 2013) between the two plates. Recall that 1) Archean rocks of the Kaapvaal Craton bears strong geochemical signatures to the Greneghona Craton and therefore suggest that these two Cratons were continue 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 been situated south of Mozambique at least during the Mesoproterozoic times (Jacobs et al., 2008 and Riedel et al., 2013). We align the two boundary faults of Archean Kaapvaal and Grunneghona Cratons (Tankard et al., 2009) and their Mesoproterozoic orogenic zones. The data is further strengthened by the new information from seismic refraction in the Limpopo Basin and the NNV (Domingues et al., 2016; Lepretre et al., 2017; Verrier et al., 2017;), and on the Beira High (Muller et al., 2016) which invalid overlap of Antarctica on these structures.

Our reconstruction of the Falkland-MEB and Southern Africa was achieved along the lines of (Curtis and Hyam, 1998; Marshall, 1994; Martin et al., 1982, 1982; Lock, 1978) and the new seismic refraction data by (Verrier et al., 2017; Lepretre et al., 2017) (figure 22). The main problem regarding Patagonia reconstruction of the Patagonia-Falkland 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 (Zaffarana et al., 2010). Currently, the amount of displacement, and the timing of the deformation remains a subject of debate. Rapela et al. (1991) suggested the regional structure to indicate NW-SE dextral strike-slip displacement without evidence of regional extension. Franzese and Martino (1998) contradicted Rapela et al. (1991) suggesting mainly oblique reverse deformation. Recently, based on field observation Gosen and Loske (2004) and Zaffarana et al. (2010) suggested that the rocks associated with the GFS do not show evidence supporting the existence of major dextral fault system. Hence, the reconstruction of the Patagonia-Falkland requires no dextral strike slip deformation along the Gastre Fault System as deformation is non-evident from field studies.

However, with the new seismic refraction results from Lepretre et al., (2017), reconstruction along the lines of Gosen 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 ~250km of strike-slip deformation along the GFS to firmly close the South Natal Valley. Contrary to Gosen and Loske (2004) and Zaffarana et al. (2010), Revillon (personal communication 2017) suggest that the GFS may not have experienced the strike-slip deformation, that such strike slip system may lie further south.

6.3(b) Antarctica-India fit

We reconstruct Antarctica and India (figure 80) on the basis of the geochronological data of (Fitzsimons, 2000; Kelly et al., 2002: Gosh et al., 2004; Biswal and Sinha, 2004; Boger, 2011). Recall that rocks of the Eastern Ghats Craton and the Rayner - Napier complexes share similar geochronogical properties (Biswal and Sinha, 2004, and Gosh et al., 2004; Boger, 2011), and the Rayner Complex extends from Enderby Land into the Mesoproterozoic rocks of the Eastern Ghats Granulite in India. Their juxtaposition is further strengthen by the continuity of Gondwanan rift basins of Godavari and Mahanadi (India), and Lambert and Robert rift valleys of Eastern Antarctica (Kelly et al., 2002 : Gosh et al., 2004: Biswal and Sinha, 2004). The ~120km overlap between India and Antarctica within Southern Bangladeshis explained by the not clearly defined limits of the India plate within the region, and the characterization of the region by Large compressional deformation.

6.3(c) **Antarctica-Australia fit**

The reconstruction of Antarctica and Australia (figure 81) is the least complicated of all the Gondwanan plates. This is due to the several Cratons and continental blocks that is identified to continue between the two plates. Our reconstruction was achieved on the basis of the geochronological of (Borg and DePaolo, 1991 and Boger, 2011). Recall that the Mawson and Beardmore Cratons can be juxtapose to their conjugates (Mason and Curnamona Cratons) in Australia (Borg and DePaolo, 1991 and Boger, 2011), that the Mesoproterozoic A (1.65-1.55Ga), Mesoproterozoic D (1.35-1.15Ga), Mesoproterozoic E (1.1-1.05Ga), can be traced to rock of similar geochronological ages in Antarctica.

6.3(d) Madagascar-Africa fit

Our model for Madagascar and Africa (figure 82), on the basis of similar ages, aligns the Pan-African shear zone separating the Vohibory complex (Tucker et al., 2014) of Madagascar to the PanAfrican shear zone in Tanzania (Collins and Pisarevsky, 2005; Reeves et al., 2014), and continue the Brava fault in Kenya with the Andreaparaty shear zone in Madagascar. This allows the Belet Uen fault to be juxtapose to the northern fringe of Madagascar.

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. The initial rifting between the two plates was accommodated within these basins in the Permo-Trassic (Catuneau, 2004; Guillocheau and 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 Abdullah, 1995). The fit also allows a good view of the extent of the Neoproterozoic granulites, of Madagascar (Vohibory domain) and Africa (The Cabo Delgado nappes of the Mozambique belt) (Bingen et al., 2009 and Tucker et al., 2014), which share similar geochemical properties. 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 early Ediacaran time (0.65–0.63 Ga Tucker et al., 2014). Recall also that the protolith of the Bur Acaba share similar geochemical and geochronological properties with the Late Archean rocks of the Antananarivo Domain (2.75-2.50 Ga) (Tucker et al., 2014) and may therefore suggest that the Bur Acaba may have been continues with the Dharwar Craton before Gondwana’s breakup.

6.3(e) Madagascar-India fit

Our reconstruction between Madagascar and India (figure 83) is along the lines of Windley (1994) Rekha et al. (2014) and Tucker et al. (2014) who provided geological evidence for the continuation of Dharwar Craton between India and Madagascar. We fit the Dharwar archean rocks in India to the archean sequence of Eastern Madagascar. Archean rocks of the Western Dharwar outcrop in Antongil and Fenoarivo in Madagascar is surrounded by Neoarchean and Paleoproterozoic rocks from the eastern margin into Antananarivo. We trace 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). 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 (figure 21). The reconstruction leads to 100km overlap between India and Africa. This is due to the poorly defined limits of the India plate in the Karachi area.

CHAPTER 7: PROPOSED MODEL OF EAST-WEST GONDWANA EVOLUTION

7.1 Proposed model of Gondwana's initial fit

The proposed initial fit of Gondwana is providing good alignment of delineated conjugate structural markers between the plates, and takes into account current published and accepted geochronogical data from the basement of the plates. The model follows earlier model (Kuster et al., 1990; Lenoir et al., 1994; Reeves and de Wit, 2000; Ghosh et al., 2004; Tucker et al., 2014) shows the equivalent of the Dharwar Craton traced of the India plate into Madagascar and possibly into the Bur Acaba of Africa and beyond (Figure 82, 84 and 85).

It also allows the full extent of the Pan-African orogenic event and the Karoo volcanism in Gondwana, and aligns Archean and Mesoproterozoic rocks in Madagascar and India (Figures 86). With regard to the fit between Australia and Antarctica, it permits a continuation of the Beardmore and Mawson Shield s in Antarctica into Australia, and continues trace of Mesoproterozoic A (1.65-1.55Ga), Mesoproterozoic D (1.35-1.15Ga), Mesoproterozoic E (1.1-1.05Ga), between Antarctica and Australia (Figures 81, 84 and 85).

In fitting India to Antarctica, our model achieves a good alignment of Archean rocks of the Napier complex and the Eastern Ghat Craton, as well as the alignment of conjugate Gondwanan rifts basins (Mahanadi and Gondavari of India, and Lambert and Enderby rift basin of Antarctica) and Mesoproterozoic rocks between the two plates (Figures 80, 84 and 85). Notice the alignment of the Vohibory Pan-African shear zone to which the Pan-African shear zone in Tanzania. The Brava faults in Kenya is fitted to the Andreaparaty shear zone in Madagascar, and the Belet Uen fault in Somalia fitted to the fault lying to the northern border of Madagascar.

The Ranotsara shear zone is proposed to continue with the Tombo faults due to their alignment and NW-SW trend, and may continue into Kenya into the Aswa shear zone. The extent of the Neoproterozoic granulites (0.65–0.63 Ga Bingen et al., 2009: Tucker et al., 2014) in Mozambique and Madagascar is also evident in our model.

7.2 Model consequence on offshore geological structures

The model is also coherent with current geophysical and geological data interpretations on 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 et al., 1981; Thompson et al., 1982; Ben-Avram et al., 2005; Gohl et al., 2011; Fischer et al., 2017),continental origin for the North Natal Valley and North

Mozambique ridge (Martin et al., 1982; Curtis and Hyam, 1998; Lepretre et al.,2017; Verrier et al., 2017;), the Maurice Ewing Bank (Martin et al., 1982; Goodlad et al., 1982; Lorenzo and Mutter, 1988; Curtis and Hyam, 1998; Ben-Avraham et al., 1995, DSDP Hole 330),the North Madagascar ridge (Schlich et al., 1974 and Goslin et al., 1981), and seismic reflection result in support of a continental origin for the Beira High (Mahanjane, 2012; Muller et al. (2016).

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

The new model apart from providing a better constraining of Gondwana's initial fit on the basis of published geochronological data and delineated structural markers, also provides a good fitting of conjugate basins of the various plates. Notice how perfectly, the Karoo sediments of Madagascar and Africa aligns, and the extent of the Karoo and Ferrar volcanism in Africa and Antarctica (Duncan, et al., 1997: Reeves and de Wit, 2000; Jourdan et al., 2005:; Klausen et al., 2009) (figure 86).

Between Africa and Madagascar (Figure 82), 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. This allows for the eastern margin of Karoo rocks mapped in SW Madagascar to be aligned with similar rocks in the Selous-Tanga Basins (Figure 86) in Tanzania which is continued 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 well seen on the satellite gravity data of Sandwell et al. (2014), and was interpreted by (Reeves and de Wit, 2000) to indicate the initial line of fracture of Madagascar away from the Africa continent.

Reconstructions along this line allows a 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 it conjugate Zambeze basin (Figure 79) on the basis of identified magnetic anomalies and fracture zones (Ségoufin, 1978; Simpson et al., 1979; Konig and Jokat, 2010; Leinweber et al., 2012). Between Antarctica and India, the Bengal basin of India is fitted to 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 (Figure 80).

7.4 Proposed evolution of the Indian Ocean

Using this new coherent and holistic starting point, we provide then the evolution of the India Ocean (Figures 87-95) in the context global plate deformation from events published in literature (with emphasis on the Tethys Ocean), to understand on the global scale the extent of these tectonic events within our chosen time period.

7.4(a) Pre-breakup history

7.4(a)i The Late Carboniferous-Early Triassic (Acadian 250-200Ma)

The collision between Laurasia and Gondwana during this age led to the formation of Pangea, and the opening of the Paleo-Tethys Ocean, which may lasted until the Early Triassic when the Tibetan block, the North Afghanistan block, and eo-Cimmerian (Lamotte et al., 2015) rifted from Greater India and collided with Eurasia, consuming the ocean between them.

The formation of the intracratonic Karoo rifting and block-faulting developed contemporaneously with the compressive tectonics recorded 261Ma in the Cape Orogeny in South (Delvaux, 1991, Watkeys, 1998). The spreading axis jumped southward to initiate rifting and opening of the Meso-Tethys between Greater India and Eurasia when the Central Afghanistan block and a number of other blocks were rifted from Greater India (Kazmin, 1985, 1989). This collision correlate with a major unconformity observed within the Karoo sedimentary units in the Early-Middle Triassic (Figure 51 and 52). The collision may have resulted in an uplift of Gondwanan blocks and widespread erosion witnessed in the Karoo Basins.

In the Tethys Ocean, the events were recorded in the Himalayan Orogenic Belt, along Eastern Arabia and northwestern Australia margin (Kazmin, 1989 and Gnos et al., 1997).

In Gondwana this period saw the deposition of the Karoo Supergroup (sand, silt, coal and continental red beds) across the supercontinent (Cateneanu, 2004; Geiger et al., 2004; Guillocheau and Liget, 2009). The Permian-Triassic period started with the development of the Karoo grabens, along the East and South African, and the Southwestern Madagascar margins (Raillard, 1990; Virloqeux, 1984; Lafourcade 1987; Watkeys, 1998 and 2002). Major rift systems were initiated and linked to large extensional fault systems that penetrated into Gondwana from the Tethyan margin (Senton et al., 2012; Kreuser, 1983, Watkeys, 1998), generating several basins including the Mozambique and the Somali Basins and reactivating older rifts structures (Virloqeux, 1984; Lafourcade 1987, Cateneau, 2004).

7.4(a)ii Mid Triassic-Middle Jurassic

In the Tethys Ocean, the collision of the eo-Cimmerian chain of blocks with the Eurasia resulted in the subduction and obduction of the Paleo-Tethys and a shift of rifting southward into Greater India leading to the opening of the Meso-Tethys (Gnos et al., 1997). On the peri-Arabian margin, the Bitlis Massif and Kaban (Taurus platform) blocks rifted from the Arabian margin (Kazmin, 1985, 1989) creating deep-water basins in place of earlier continental rifts, separating a number of carbonate platforms from the continent.

The Meso-Tethys was finally closed in the Middle to Late Jurassic when the central Afghanistan block together with the other blocks collided with Eurasia. The spreading axis shifted southward subsequently initiating rifting and opening of the Neo-Tethys Oceans between the remaining Greater Indian block (Gondwana) and Eurasia. According to (Gnos et al., 1997), the Burma-Malaya, and Sumatra continental blocks rifted from Northwestern Australia, and created an oceanic space between Greater India and North Australia at this age in the Late Jurassic. The opening of the Neo-Tethys Ocean and the ocean between Greater India and North Australia is contemporaneous with the Late Jurassic opening of the India Ocean.

The Middle Jurassic marks a period of major magmatism (The Karoo igneous) in Gondwana, which was witnessed across most of Gondwana’s blocks. The origins and role of the Karoo volcanism in the breakup of Gondwana is still under debate [See chapter 2(a) and (b)]

7.4(b) Breakup and formation of first oceanic crust

7.4(b)i Middle-Late Jurassic

During the Late Jurassic, the East-West separation of Gondwana occurred contemporaneous with the closure of the Meso-Tethyan oceanic occurred (Kazmin, 1989), when the Central Afghanistan block (Cimmeria plate) collided with Eurasia, and the oceanic space between them was finally obducted and subducted under Eurasia (Kazmin, 1989 and Gnos et al., 1997) (Figure 51). The Neo-Tethys Ocean was opened between Northwestern Australia and Greater India, and between peri-Arabia and greater India. The Eastern Ophiolites of Oman (Masirah Island Ophiolite of Eastern Oman) records the early formation of Neo-Tethyan Ocean between Eastern Arabia and Greater India in the Late Jurassic (Gnos et al., 1997). These Ophiolitic belt is characterized by ocean floor fragments created during the Late Jurassic-Late Cretaceous (C34) (Gnos et al., 1997).

In the Indian Ocean, the break-up 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 basins (and Argo) basins. The magnetic anomalies identifications 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. The Cenozoic evolution history of the MozambiqueAntarctic corridor is after Bernard et al. (2005).

Davis et al. (2016) interpreted magnetic anomalies M24Bn through to M0r about the extinct ridge in the Somali Basin. They noted their magnetic interpretations are 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 setallowed them to match the older magnetic anomaly picks by defining a pole of rotation for a single and cohesive East Gondwana plate. However, following magnetic anomaly M15n, 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 87 to 89). We then allowed Madagascar-India-Sri Lanka to move free from Antarctica-Australia. This occurred around M15n as observed earlier by Davies et al. (2016). Subsequently, we defined independent motions for Antarctica-Australia, and Madagascar-India-Sri Lanka using data from their individual basins.

Leinweber and Jokat (2012) and Konig and Jokat (2010) defined comparable spreading rate in the Mozambique Basin, they found spreading half-rates of 23.5 km/Myr from M26n.1n (155 Ma) to M22n.1n (149 Ma), and of 21 km/Myr from M22n.1n (149 Ma) to M12.r.1r (138 Ma). In the Somali Basin Davis et al., (2016) defined spreading 1/2 rate of 25km/Myr from M24B to M21n, rising to 63km/Myr between M21n and M10Nn.1n, 27km/Myr between M10Nn.1n and MOr.

In Mozambique basin, we suggest the age of the first oceanic crust corresponds with the intrusion of the rhyolitic magma on top of the Belo Formation (Figure 55), and with the deposition of the Kidulgallo shales and marls on top of the Amboni Formation in the South Tanzanian Basin. In Morondava basin the age corresponds to the deposition of Duvalia Marl (Mudstones) on top of the Sakanavaka Formation (sandstones).

7.4(b)ii Early Cretaceous-Mid Cretaceous (135Ma-125Ma)

This period saw large scale plate re-organisation across the world (Moulin andAslanian, 2010). The Hauterivian/Valanginian boundary is marked by a re-organization in the Pacific Ocean, the first oceanic crust in the South.

The age also corresponds with large alkaline volcanic emplacement of the Explora Wedge of Antarctica. Volcanic intrusive were recorded along the Lebombo Monocline, the Bumbeni Complex intruded at 133±5 Ma (Allsopp et al., 1981). In the Ruhuhu basin, near the shores of Lake Malawi, kimberlite pipes and alkaline diabase dykes have been recorded intruding the Karoo sediments (Tankard, 2009; Kreuser, 1983). Alkaline volcanic intrusions within the Western Ophiolite Belt of Pakistan (Kazmin, 1989) was also recorded at this time. On the Eastern Ophilites belt of Oman, Alkaline, Harzburgitic and Granitoid intrusions are emplaced.

The Rajmahal Traps also intruded in the Bengal basin at this age (Vijaya and Bhattacharji, 2002).

It is also the time Etendeka-Paranã flood basalt in the western Gondawana.

The period saw the African plate experienced significant intraplate deformations along old Precambrian suture zones during this period (Fairhead, 1988; Reeves and de Wit, 2000; Moulin et al., 2010). In the north within the Benue Trough 85km extensional, folding, and sinistral strikeslip fault deformation (Fairhead, 1988; Moulin et al., 2010) have been estimated. In the boundary between Nubian and Austral blocks the Central African shear zone is recognized, extending about 2000 km across Africa from the Atlantic coast in the Gulf of Guinea through Cameroon, Chad, the Central African Republic and into Sudan (Guiraud et al., 2000; Moulin et al., 2010). Early cretaceous grabens in Zambezi, inhaminga, Urema, Pamira, Chedinguele (Mozambique) were reactivated during this age (Raillard, 1990; Sahabi 1990 and Watkeys, 2002).

In the Indian Ocean, the period led to the formation of Curvier, Perth and Gascogne basins on the northwestern Australian margin (Veevers et al., 1988). Is still not clear the blocks that were rifted from the Northwestern Australian margin leading to the opening of these three basins at this time.

On the Antarctic margin, it caused the separation between the Elan Bank and East Antarctica, leading to the formation of the Enderby Basin between the Elan Bank and Antarctica. 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. (2003, 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 anomalies in the west of the basin suggest 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 estimated full spreading rates of 7.5 km/Myr at 135 Ma, increasing to 15 km/Myr at 125 Ma, and finally accelerating to 37.5 km/Myr by 120.6 Ma between India and East Antarctica in the Princess Elizabeth Trough region.

In our model (Figures 89-91), matching the Mesozoic anomalies in the Mozambique and Somali Basins, led to initiation of rifting between India-Elan Bank and East Antarctica around magnetic anomaly M10n (128.93 Ma). This may mean seafloor spreading may have begun around this time and the oldest magnetic anomaly between the Elan Bank and East Antarctica maybe around anomaly M10n.

The Early Cretaceous also saw, together with the Austral Segment of South Atlantic (Moulin et al., 2010), the formation of first oceanic crust in the South Natal Valley at magnetic anomaly M10. Marine transgression reached the southern end of the African block with the creation of the South Natal Valley.

In the Somali and Mozambique Basins, seafloor spreading continued with major marine transgression accompanied by intermittent regression occurring in the two basins Walford et al. (2005). The Early Cretaceous was typified by development of widespread transgression within the Eastern Africa. The period saw the deposition of the Maputo Formation, which represents the initial flooding of the shelf after the formation of the first oceanic crust offshore the Limpopo Basin. There is evidence of volcanic activity in the Early Cretaceous in parts of the Mozambique Basin: alkalic lavas are observed in the Maputo Formation (Figure and 61 and 62).

7.4(b)iii Cretaceous (M0-C34) (~125-85Ma)

The Barremian/Aptian Boundary is marked by the inception of the Cretaceous Quiet Magnetic period and the start of a global main plate reorganization, which both will end during the Albian time. This is the time of the cessation of the Pacific-Phoenix ridge (the Nova-Canton Trough) (Nakanishi and Winterer, 1998) while the spreading ridge between the Manihiki and the Hikurangi plateau (Osbourn Trough) started (Aslanian, Pers. Comm. 2017), and the beginning of the movement of Iberia Plate, with the opening of the Gulf of Biscay.

Between 95 Ma and chron 34, a series of events occurred worldwide: the start of a spreading system in the Tasman Sea (Hayes and Ringis, 1973; Gaina et al., 1998), 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 (Aslanian, Pers. Comm. 2017), 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) and in the North and Central Atlantic Oceans (Olivet et al., 1984; Olivet, 1996) or worldwide (Scotese et al., 1988, Olivet et al., 1991).

In the Indian Ocean, the accretion in the Curvier, Perth and Gascogne basins stopped at M0, Madagascar-Greater India-Sri Lanka block stopped its southward drift from Africa and consequently seafloor spreading in the Somali Basin had stopped. A Low rate left-lateral strikeslip motion was initiated between Indian 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 (Davies et al., 2016).

Following Frey et al. (2000), we initiate the beginning of the emplacement of the Southern Kerguelen Plateau around 120Ma, contemporaneous with the emplacement of the Maud Rise, South Mozambique Ridge, Agulhas Plateau, and north of Astrid Ridge (Figures 93 and94). The Southern Kerguelen Plateau was initially attached to the Indian plate until a northward ridge jump, shortly before C34, attaching the plateau to East Antarctica. The Perth Abyssal Plain and the East Enderby Basin formed a continuous spreading system at this time (Gibbons et al., 2013), until a ridge jump initiated to commence seafloor spreading Elan Bank and India at C34, in agreement with Jokat et al. (2010). Jokat et al. (2010) 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.

Following Eagles and Hoang (2013), the transtensional deformation between Greater Indian and Madagascar resulted in a southward motion of Greater India relative to Madagascar, before a counter-clockwise rotation to collide with Eurasia. Seafloor spreading in the Mascarene basin started 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 crust was affected the most, becoming the locus of convergence which led to the emplacement of the ophiolites in East Arabia and West Pakistan (Kazmin, 1989 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 and Karsten; Martin, 1987; Gohl et al., 2001, 2011). These four ridges overlap at the Southern Mozambique Ridge at M0 (Parsiegla et al., 2008) (Figure 92). 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 et al. (1981), the position of these ridges with respect to anomaly 34 indicates that they are older than C34.

In the Mozambique Basin, the period saw the deposition of the Lower Domo Shales, which represents major Mid-Late Cretaceous transgression of the shelf comprising marine mudstones with some bands of arkosic sandstones. The sand-prone Domo Sandstone and the Upper Domo Shale (Late Turonian –Santonian) overly the Domo Sand. The Upper Domo Shale is composed of marine shales and clays interbedded with thin glauconitic sandstone and siltstone beds (Salman and Abdula, 1995).

7.4(b) iv Late Cretaceous (C34-C32) (~83.9-75Ma)

At the end of the Cretaceous Quiet Magnetic period, breakup and first oceanic crust are recorded between Australia and Antarctica (Cande and Mutter, 1982 and Veevers et al, 1990), and Antarctica-Elan Bank and India (Gaina et al., 2012).

Oceanic plateaus (Conrad Rise, Crozet Ridge, Del Cano Rise and the South Madagascar Ridge) became emplaced during this period along the Southwest Indian Ridge (Schlich et al., 1974 and Goslin et al., 1981; Sahabi, 1993).

The Del Cano Rise according to Goslin et al. (1981) is a conjugate feature of the southern Madagascar, due to the overlap of these two highs in pre-anomaly 24 reconstructions Ridge across the Southwest Indian Ridge (Figure 94). According to them, both features, were formed at the same time along the axis of the Southwest Indian Ridge. The Southern section of the Madagascar Ridge is composed of an anomalous thickened oceanic crust (Schlich, 1975; Goslin et al., 1981). The Southern Madagascar Ridge and Del Cano Rise may have been emplaced along the Southwest Indian Ridge during a period of slow spreading in the Early Eocene (chrons 24-23) (Schlich, 1975; Goslin et al., 1981; Royer and Patriat, 1987), at the junction between the two differently oriented Southwest Indian and Southeast Indian ridges (Sahabi, 1993).

The Crozet Plateau is located between 45°57’ to 46° 29’S and 50°10 to 52°19’E in the Southern Indian Ocean, composed of two distinct highs emplaced by the Southeast Indian Ridge (Goslin et al., 1981). The plateau is bounded to the southwest by anomaly 32 to the southwest and by anomaly 31 to the northeast (Schlich, 1975). Goslin et al., (1981) and Royer and Patriat (1987) therefore proposed that the two plateaus may have been initiated around this t ime, possibly due to anomalous volcanism along the Southeast Indian Ridge.

South of the Del Cano Rise and Crozet Bank lies the broad WNW-ESE trending Conrad Rise consisting in part, of the Ob, Lena and Marion Dufresne volcanic chains. According to Royer and Patriat, (1987), the Ob, Lena and Marion Dufresne plateau may have been emplaced contemporaneous with the Crozet plateau (conjugate structures), during a period of major reorganization of the plate boundaries in the Cretaceous Quiet Zone.

In the Tethys Ocean, the subduction zone initiated north of the Africa-Arabian plate and the Eurasian plate (Kazmin, 1989), which subsequently guided the emplacement of the Eastern Oman and Western Pakistan Ophiolites, leading to the closure of the Neo-Tethys Ocean between Africa-Arabia and Greater India. The spreading axis between Madagascar-Greater

India and Africa jumped eastward to initiate seafloor spreading between Greater Indian and Madagascar at C34.

The Late Cretaceous was typified by a development of widespread transgression along Eastern Africa (Mougenot et al 1986; Raillard, 1990; Salman and Abdula, 1995). The Lower Grudja Formation (Campanian-Maastrichtian) composed of dark grey shale interbedded with beds of glauconitic sandstones and the carbonate rich Upper Grudja Fm (Paleocene) were deposited during this period.

7.4(b)v C32-C20 (75-45Ma)

Between Campanian and Ypresian time, the convergence between Africa and Eurasia stopped (Sioni, 1996; Fidalgo-Gonzàlez, 2001; Pellen, 2016) and the opening between Greenland and Labrador starts. It is the time of a change in direction of the oceanic Fracture zones in over the oceans.

The Lutetian time is marked by a worldwide major change, in the Pacific Ocean (Duncan et Clague, 1985; Caress et al., 1988; Hey et al., 1988; Lonsdale, 1988) in the Central Atlantic Ocean (Olivet et al., 1984) and in the Indian Ocean (Cande et Mutter, 1982; Patriat et Segoufin, 1988).

The Mascarene basin stopped its accretion in Paleocene time at C27, and a ridge jump initiated seafloor spreading between Seychelles and India with the start of the Reunion hotspot (Figures 94 and 95). This hotspot seems to be connected with the Deccan Traps (66Ma Schcene et al., 2016) in India, and the basalts on the Seychelles microcontinents (Jaeger et al., 1989; Knight et al., 2003). The Seychelles plateau is bounded to the south by the Mascarene Plateau and Saya de Malha bank underlained by metadolerite and epidiorite of Late Precambrian age (650 Ma, Mart, 1968). The Chagos-Laccadive and the Ninetyeast Ridges were initiated at this period (Ashalatha et al., 1991). In the Tethys Ocean, volcanic intrusions were also recorded in the Western Ophiolite Belt of Pakistan (Gnos et al., 1997) and correspond with the final obduction of the Western Pakistan Ophiolites. The soft collision of India and Eurasia commenced around this age (Hinsbergen et al., 2012).

In the Mozambique Basin, the period was characterized by major flooding and widespread deposition of carbonates in the Mozambique Basin (Mougenot et al 1986; Salman and Abdula, 1995), leading to the deposition of the Cheringoma Formation (Eocene). In the Oligocene, the East African margin was uplifted, accompanied by marine regression (Mougenot et al 1986).

7.4(c) Comparing with other models

The trajectory in our model (Figure 96 and 97) is compared to that proposed by Reeves et al. (2015), Gaina et al. (2013), Leinweber and Jokat (2012) and Sahabi (1993). Due to the fact that the evolution depends on the initial position of the plates, these models differ, especially for the first movements.

Madagascar evolution (Figure 98a and b):

For the evolution of Madagascar, Leinweber and Reeves et al. (2915), starts with an initial overlap of Madagascar on Africa between 180Ma to 160Ma before it begins a southward drift to its present position. That of Gaina takes a more Southeast drift throughout its evolution to its present position, whiles the model of Sahabi begins first with an initial southeastward movement and a subsequent southward drift.

Our evolution may seem similar in direction with Reeves's model, but the positions of Madagascar from the fit, where Madagascar overlaps Africa, to Barremian are very different. Reeves's model describes a stop in the souithwards movement of Madagascar between Berriasian and Barremian times. Gaina's model implies a different initial evolution, with a movement slightly eastern, due to its more North-south position of Madagscar at fit time. The timing is anyway different as the movement of Madagascar start later, at Bajocian almost ends at Barremian. During the evolution, Madagascar is situated eastward to our positions. Much greater differences are observed with the Leinweber and Jokat models, which describes a zig-zag evolution implying a compressive event until the Oxfordian. A less pronounced inverse zig-zag is described by Sahabi's Model, as the fit position of Madagascar is more to the north and less North-South oriented. Since Berriasian, the positions of Madagascar are very similar to our model.

Antarctica evolution (Figure 99a and b)

Three models opted more or less for an overlap of Antarctica on Limpopo basin. These hypothesis imply 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 which is in coherence with the new geophysical date in Limpopo and Natal basins is the one of Sahabi. It has slight differences with our model as our fit is less tight due to the fact that our model takes into account the continental nature of the Beira High.

Madagascar and Antarctica evolution

Unlike (Smith and Hallem, 1970; Konig and Jokat, 2006; Eagles and Konig, 2008; Leinweberet al., 2012; Seton et al., 2012; Torsvik et al., 2012, 2008; Gaina et al., 2007,2013,2015; Reeves et al., 2002, 2015), who proposed distinct poles for Madagascar and Antarctica from breakup to their present position, our model kept a single unit East Gondwana, and visually matched the magnetic anomalies and fracture zones in the Somali and Mozambique basins until we can no longer match the data in both basins maintaining a single East Gondwana Unit. The subsequent motion were constrained using data from their individual basins this occurred around M15 in agreement with the observation of Davies et al. (2016). At M15, we could no longer maintain a cohesive unit and therefore allowed the Madagascar-India-Sri Lanka circuit to move free from Antarctica-Australia. Our model is in agreement with the mechanism of Gondwana based on their magnetic anomaly pickings.-

CHAPTER 8: DISCUSSION

8.0 DISCUSSION

This work introduces a new model of Gondwan with significant implication on some of the scientific questions earlier discussed.

The role of the Karoo volcanic event

Previous models (Cox, 1992; Klausen, 2009) identified Seaward Dipping Reflectors (SDR's) in the Limpopo Basin. Cox (1992) proposed the basin's development to be related to a plume, with resultant breakup, extensive volcanism, and subaerial spreading. He equated the conjugate of the Lembobo monocline to the Explora Wedge of Antarctica (Hinz 1981) emplaced at time of the Karoo event.

Two possible mantle plume source positions were proposed for this event.

1. The triple junction of Northern Lebombo, the Save–Limpopo and Okavango dyke swarms intersection (Hastie et al., 2014).
2. A much broader and wider plume source, about 2000 km in diameter situated at the juncture between Antarctica and the Lebombo to account for the magmatism of both the Dronning Maud Land (Burke and Dewey, 1973; White and McKenzie, 1989; Duncan *et al*., 1997).

Our new model, in the agreement with the new seismic refraction results from (Domingues *et al.* 2016; Verrier *et al*., 2017; Lepretre *et al*., 2017), suggests a continental origin for the North Natal Valley and the Limpopo Basin, in contrast to the suggested oceanic origin by (Cox, 1992; Jourdan *et al*., 2007; Klausen, 2009; Leinweber and Jokat, 2011, 2012, Hastie et al., 2014). We agree with Flores (1975) and Storey *et al*. (1995). Flores (1975) observed that instead of a continuous sheet of Karoo effusive in the Limpopo basin, the basin maybe characterized by the existence of a series of parallel, trending fractures issuing ever younger magma from west to east. Storey *et al*. (1995), proposed that Karoo event only played an indirect role in the break-up of Gondwana by thermally weakening lithosphere and inducing local rifting but not resulting in breakup between east and west Gondwana.

This implies that the volcanic event did not provided the needed trigger for the breakup of Gondwana.

In addition, the oldest well dated magnetic anomaly in the Antarctic Riiser Larson Sea, the Somali Basin and the Mozambique basin is M25. Older interpreted magnetic anomaly ages all relate to within the Continent Ocean Transition Boundary from our interpretation of new seismic data. As Jokat *et al*., (2003) already suggested the large time delay between the volcanic event and the initial separation of Gondwana indicates the event did not provide the essential trigger for the spreading of Gondwana, but may have controlled the ultimate positioning of major fault systems within the supercontinent, which may have subsequently being exploited to disintegrate the supercontinent.

The source(s) of Karoo volcanic event

Forty years ago, Bristow (1980) observed that the Karoo basalts show both enriched and depleted mantle sources, and therefore predicted that these basalts have being sourced differently. He also observed that the rhyolites show abnormally high Sr and Ba components, with high enrichment in K and Na compositions. He therefore predicted that these rhyolites may have been sourced from the partial melting of previously underplated basaltic magma that may have contaminated the magma leading to the high Sr, K and Na contents. His work reinforces the different source origins of the Karoo magmas, and explains the volcanic episodes as a complex interactions of mantle stresses below the lithosphere and within the African plate. Some people have linked this to subduction zones along the paleopacific margin.

Similarly, the relatively long duration of the event, lasting about 10Ma, and on the lack of preservation of bulk primitive melt compositions in the Karoo magma play against the arguments for a possible plume source for the Karoo event and may favour asthenospheric or enriched continental mantle source for the magma (Watkeys, 1998; 2002; Klausen, 2009; Hastie et al., 2014).

Indeed, the generation of the large volume of magma during the event maybe explained by the tectonic heritage of the crust along the margins (Mozambique belt and at the Southern African region). As a result of the process of compression and subduction of the Panthalassa oceanic crust in southern Gondwana, the continental lithospheric mantle could become enriched due to mantle warming from continental insulation (Nicolas +de Wit+ Stern). This, coupled with rifts reactivation (note the Tethyan rift was propagating south) may trigger decompression and release of large magma. Reactivation of shear zones in response to distant stress has been observed by Bonin, (2004) to trigger alkaline intraplate magmatism. He notes major shear zones are characterized by a higher heat flow due to a thinner lithosphere as it is the case in rifts, even with weak displacement. The shear movement produces linear lithospheric delamination during the reactivation, which in turn lead to partial melting and magma intrusion (Liégeois *et al*., 2003). Therefore strain heating may have played a significant role in triggering crustal and mantle anataxis. This process according to Dumoulin *et al*. (2000) occurs preferentially along domains with contrasted lithosphere where small-scale convection become enhanced. Furthermore, this process seems self-enhancing (Dumoulin *et al*., 2004): the reactivation generates a linear delamination favouring partial melting, which in turn favors movements, delamination and partial melting. The large regional stress may then reactivate the preexisting shear zones, generating linear delamination along them with partial melting at possibly the lithosphere–asthenosphere boundary to produce the more enriched magma (picrites and enriched basaltic magma and the tectonic movement allows the upward movement of the magma. A part of the magma may reach the surface, but a larger part may remain at depth, underplating the crust, provoking partial melting to form the depleted and contaminated basaltic and rhyolitic series.

Extra-heat brought in by a mantle plume may therefore not be necessary here. This process may results in deposition of large volumes of continental flood basalts onto the crust without necessary generating plate breakup. This could explain why large volume of magma could intrude along the Lebombo-Limpopo area without generating continental breakup.

Age of Gondwana breakup

We highlighted in chapter 4.2 the general differences in the period predicted for oceanization in the Somali and the Mozambique Basin (Figures 54 and 55). Rifting age in the Somali Basin from starts from as early as Late Triassic to Oxfordian. However, some models predict oceanization to have commenced with deposition of the Andafia beds in the Toarcian (183-176Ma), leading to an overlap between oceanization and rifting between Toarcian and Callovian. Similar observations are recorded in the Mozambique Basin, where, the rifting started in the Late Triassic and ended in the Late Jurassic, but oceanization is also sometimes argued to have started in the Early Jurassic (eg Burke and Dewey, 1973; Duncan *et al*., 1997; Watkeys, 1998, 2002; Eagles and Konig 2008; Klausen, 2009; Hastie et al., 2014; Gaina *et al*., 2013; König and Jokat, 2010; Leinweber and Jokat, 2011, 2012), with the Karoo magmatic event leading to overlap of possible rifting and oceanization at the same time between late-Early Jurassic and Middle Jurassic.

By contrast the interpretation that prefers the rifting to have ended in the Early Jurassic Karoo magmatism, our model proposes rifting may have continued in the Mozambique basin until Late-Middle Jurassic (Figure 100). This then implies that the deformed Belo Formation containing the conglomerates and continental red beds that overlie on the Karoo volcanics in Mozambique represents a synrift formation, and that initiation of oceanization may have started a little before or around M25 in the early-Upper Jurassic. This interpretation agrees with the latest published seismic data in the Offshore Zambezi Delta Depression by (Salazar *et al*., 2013) (Figure 101). On the South Tanzania basin, the rifting causing breakup and initiating oceanization may have started in the late Triassic and ended in the Callovian, initiating drifting onwards (Figure 102).

As we already discussed, there is a good correlation of the tectonic events in the Tethys Ocean and the Indian Ocean: the late Jurassic (157Ma Gnos *et al*., 1997) seafloor fragments of the Eastern Ophiolites belt of Oman recorded in the opening of the Neo-Tethys Ocean. We saw that the M41 event, supposed to be present in the Mozambique Basin, was not recorded in the Tethys Ocean, neither in the Central Atlantic Ocean which were operating during that period. On the contrary, the opening of the Neo-Tethys Ocean correlates with M25 (Veevers *et al,* (1988) or M26 (Fullerton *et al*., 1989) first oceanic crust in the Argo Basin (The Northwestern Australian Basin), and with the confidently dated oldest magnetic anomaly in the Mozambique and Somali basins M25. In the Central Atlantic, Labails *et al*. (2010) observed a major change in direction of plate propagation from NW-SE to WNW-ESE (Figure 103).

Sedimentary insights for the age of breakup

A general hiatus or unconformity is observed along the East African margin and on Madagascar in the Aalenian and Bajocian. This has been linked to an uplift event experienced along these margins (e.g. Kejato, 2003). At this stage, an early carbonate platform had developed along Madagascar and South Tanzania basins under shallow marine conditions and sedimentation flanked the edge of the margins. The Mid Jurassic shallow marine deposits of Morondava and Majunga, including the limestones of Andafia and Bemarah a formations, and bituminous shales, were deposited at this stage of the margins evolution (figure 102). A similar age carbonate sequence is identified in the North Rovuma Basin with the Mtubei Limestone and Mandawa Series (Figure 51). No equivalent of these carbonate sequences has been recognized in the central and south Mozambique basin. The Lupata Formation, which contains some marine units, represents the first marine influences in the Central Mozambique Basin in the Upper Jurassic. The age equivalent of the carbonate sequence is Belo Formation, consisting of continental red beds, conglomerates and weathered Karoo basalt. The Belo Formation rests unconformably on the Karoo volcanics.

Following the early platform stage leading to the deposition of the Andafia limestones and Bemaraha formations (sands, limestones), most field workers associated these sandstones and carbonates with continental breakup and oceanization (Hankel 1994, and Geiger *et al*. 2004) arguing that it marks the first major marine incursion in the Somali basin. A critical observation of the lithologies and the depth of which these sediments were deposited challenges this view.

Firstly, the observation of a first major marine incursion does not necessary warrant continental breakup.

Secondly, these sandstone and carbonate are shallow water deposits; the maximum depth to which carbonates are deposited is around 2km. The rifting of about 30km continental crust to a depth of about 2km will require further rifting and subsidence to cause its breakup. The early carbonate platforms may indicate the first major marine incursion or marine life, but continental separation between East-West Gondwana may have occurred latter. The stratigraphic sequence supports this analogy, and indicates that even deeper sedimentary lithologies (Duvalia marls and shales, and the Kidugallo marls) were deposited during the Callovian. The deep sediments of shales and marls were deposited as progradational wedge along the margins.

The deep sediments (shales and marls) would overstep a newly formed oceanic crust that formed along the margin at M25, the oldest anomaly so far identified in the Somali basin.
In the Mozambique coastal and offshore areas, sedimentation associated with this stage is during Late Jurassic/ Early Cretaceous Lupata Formation. In Morondava basin, the stage corresponds with the deposition of Duvalia marls and shales during the Callovian times (Kejato, 2003). In the Mandawa basin, this stage corresponds with the deposition of the Kidugallo marls or the Mitole Formation (figure 51). In north Rovuma basin, this stage corresponds to the deposition of the Mandawa series. These observations agree well with the accretion of first true oceanic crust in the Mozambique and Somali Basins at M25 and our studies in the Tethys Ocean.

Aseismic ridges

Our new model is coherent with current knowledge of aseismic ridges.

On the Mozambique Ridge, the model seperates the ridge into continental north (Lepretre *et al*., 2017, Moulin *et al*. submitted) and oceanic south (Gohl *et al*., 2011; Leinweber and Jokat, 2011). The southern oceanic nature may be emplaced due to excessive volcanism at a Triple Junction (Aslanian, 1993; Georgen, 2008).
For the Madagascar Ridge, following Schlich *et al*. (1974) and Goslin *et al*. (1981), we subdivide the ridge into oceanic south and a possible continental north. The southern oceanic origin for the ridge is in agreement with the seismic refraction analysis of Goslin *et al*. (1981), who

identified depth to Moho at14km across the southern part of the ridge. Recall from chapter 5.1 that their calculation of the depth to Moho from the seismic refraction profiles showed that the thickness of the crust varied from south to north. In the southern part of the ridge, south of 32°S, the Moho is located at 14 km (Goslin *et al.*, 1981). Between 32°S and 30°S, it is located at a depth of 22 to 26 km (Recq *et al.*, 1979; Goslin, 1981). Their data did not extend north of 30°S, and therefore, the Moho in this area is unknown. For the northern part of the ridge, our model predict extended continental origin for the extending northward beyond 30s, contrary to the strongly anomalous oceanic crust preferred by Goslin *et al.*, (1981), and the oceanic origin suggested in the models of (Leinweber *et al*. (2012), Seton *et al*. (2012), Torsvik *et al*. (2012, 2008), Gaina *et al*. (2007, 2013, 2015), Reeves *et al*. (2002, 2014, 2015), Davies *et al*. (2016). There is enough space created in the initial fit to accommodate the north part of the ridge.

The alignment of the Madagascar plateau with the Del-Cano and Conrad plateaus in our model suggests that they may have been formed 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 *et al.*, 1981; Goslin and Patriat, 1984) or due to hotspot activity between 90Ma-70Ma.

For the Agulhas Plateau, our model in agreement with seismic data interpretations by Barrett, (2001), who identified a main crustal layer with velocity 6.72 km/s for, the model predicts oceanic origin for the plateau, emplaced after the separation of the Falkland Plateau from southern Africa. The plateau overlaps with the South Mozambique, and the Maud Rise at magnetic anomaly MOr, suggesting they may have been contemporaneously emplaced, possibly at a tipple junction, as previously suggested by (Konig and Jokat, 2010, Leinweber and Jokat, 2012).

In agreements with seismic and geochemical studies of Alibert (1991), Charvis *et al* (1995), Gregoire *et al*. (1998), our model predicts an oceanic origin for the North and Central Kerguelen Plateaus. According to Watson *et al*. (2016), the northern part of the plateau may have been emplaced around 42Ma, and the central part emplaced during the peak production of the Kerguelen hot spot, when it extruded voluminous magma to form the Southern and Central parts, and the Broken Ridge, around 105-95Ma (Frey *et al*. 2000).

Recall basalts recovered from ODP Leg 119 (sites 738–746), 120 (sites 747–751) and 183 (sites 1135–1142) sites give an oldest age of 119 Ma for the southern Kerguelen Plateau (Duncan, 2002), indicating the emplacement of the magma around this time. In our model, the oceanic

South Kerguelen Plateau emplaced around magnetic anomaly M0r (110–119 Ma), as proposed by Duncan (2002). The South Kerguelen Plateau began forming contemporaneously with the emplacement of the Maud Rise, South Mozambique Ridge, Aqulhas Plateau, and the North Astrid Ridge (Frey *et al*. 2000). Consequently, we consider these ridges to be of oceanic origin, in agreement with current knowledge on these ridges (Gohl *et al*., 2011; Leinweber and Jokat, 2011; Leinweber and Jokat, 2012; Watson *et al*., 2016).

However, garnet-biotite gneiss was recovered on the Elan Bank, southeward of Kerguelen plateau, with similar geochemical characteristics with the Wallaby Plateau, and the Naturaliste Plateau) which may suggest these plateaus are fragments of continental crust (Gaina *et al*., 2007 and Watson *et al*., 2016).

For the question of the nature of the Beira High, our model, in agreement with the new seismic refraction data of Muller *et al*. (2016), considers the ridge to be of continental in origin and leaves space for its accommodation.

The Precambrian Seychelles plateau is accommodated between Madagascar and India.

Recent Archean zircons identified by Ashwal et al. (2017) beneath Mauritius Plateau allowed them to propose the Mauritius continental plate spaced between Madagascar and India. However, clear fracture zones are identified between the two plates indicating that the Madagascar and the plates separated from without any major plate plate between them (see figures 104 and 105). In figure 105 we highlight the evolution of the India plate from Madagascar following the fracture zones. This first require the closure of Seychelles and India at magnetic anomaly C28, followed by the the Mascarane Basin. Our reconstruction suggest the archearn rocks may be part of the North Madagascar Plateau or fragments of India as it continued it northwards drift from Madagascar. Hence the Mauritius Plateau may not be required between the two plates.

CHAPTER 9: CONCLUSION AND OUTLOOK

9.0 CONCLUSION AND OUTLOOK

9.1 Summary

In this study, we present a new kinematic model of Gondwana initial fit and evolution. The formation of Gondwana during the Pan-African Orogeny and its subsequent enlargement to Pangea fragmentation in the Mesozoic saw the largest unit of continental crust on earth live for more than 300Ma, but the question of the initial geometry of this super-landmass and its evolution through time, remains unanswered and a challenge to geologists and geophysist. Any attempt to describe the plate tectonic history of Gondwana must first start with a discussion of the initial fit of the tectonic plates. We present analysis of current reconstruction models of the Indian Ocean to examine their consequences and underlying reasons. We examine 30 published reconstruction models, comparing them and look at their consequences on the passive margins, the first oceanic crust, the intraplate deformation and prediction on the nature and origin of the aseismic ridges. These models present a number of gaps, overlaps and misfit of major structural and Cratonic bodies, and raises critical scientific questions in their full-fit reconstruction. The general problem in these models have been highlighted and grouped them into broad families.

We discuss the major scientific questions currently unanswered in the Indian Ocean, responses to which remains critical to the determination of the ‘’true’’ position of the Gondwanian plates and its evolution through time. These questions include, but not limited to;

1. What is the original geometry of Gondwana?
2. What drove the origin of Gondwana’s breakup?
3. What is the role of the Karoo magmatism in initiating the breakup of Gondwana and first oceanic crust?
4. What is the age span of the rifting event in Gondwana leading to breakup?
5. Where is the Continent-Ocean Transition boundary in the Mozambique Basin?
6. What is the consequence of published reconstruction models on the East African, Antarctic and Madagascan passive margins?
7. What is the age of the first magnetic anomaly along the East African margin?
8. What is the nature and origin of the Mozambique and Madagascar aseismic ridges?
9. What is the nature of the crust in the Limpopo basin?
10. What is the role of the tectonic heritage?

A compilation of onshore and offshore geological and geophysical data in the Indian Ocean was undertaken, to grant us understanding of the work that has already been done, and to identify the main challenges and incoherencies that exist. Geological information on all the basins in the Indian Ocean was gathered; the age predictions of the rifting events, the first oceanic crust, the oldest magnetic anomaly, and breakup ages were all compiled and analyzed.

A compilation of the lithotectonic sequence of all the Karoo basins and the Karoo event along the East African margin, and Madagascan margin has been examined, to understand their evolution to this present age. The rift ages and tectonic evolution of all the basins were examined and the incoherence between the ages noted for both the rifting and oceanization. The observed incoherencies were reexamined and reinterpreted.

The Karoo magmatic event and its association with Gondwana breakup were investigated and the current data available compared with other information available in the Mozambique basin and along the East African margin. The role of Karoo volcanic event is interpreted as not providing the needed trigger for Gondwana breakup in agreement with previous models (Storey, 1995, and Jokat *et al*., 2003), but rather, it may have controlled the positioning of large fault systems within the Supercontinent which may have been further exploited by a later divergent mantle flow, which may have caused the final breakup of Gondwana..

To resolve the question of the age of the first true oceanic crust in the Indian Ocean we searched and compared major tectono-thermal events within the surrounding oceans. These oceans were operating before Gondwana's breakup and therefore a major event like Gondwana's breakup would impact these oceans (Tethys and Central Atlantic Oceans). The search indicate a major tectono-thermal impact at M25. The late Jurassic (157Ma Gnos *et al*., 1997) seafloor fragments of the Eastern Ophiolites belt of Oman recorded the opening of the Neo-Tethys Ocean. This event correlates with M25 (Veevers *et al,* (1988) or M26 (Fullerton *et al*., 1989) first oceanic crust in the Argo Basin (The Northwestern Australian Basin), and with the confidently dated oldest magnetic anomaly in the Mozambique and Somali basins M25. In the Central Atlantic Labails *et al*. (2010) observed a major change in direction of plate propagation from NW-SE to WNW-ESE. However, no record of the M41 event was made in these oceans.

Extensive study of onshore and offshore geological and geophysical data published and newly acquired within the framework of the PAMELA project was undertaken to produce a **holistic model of East and West Gondwana's initial fit**.

Our holistic model is coherent and respect current knowledge we have about 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.

Between Africa and Antarctica, we present a model that accommodates the Beira High continental crust and the North Natal Valley and the continental North Mozambique Ridge. The model shows the extent of the Archean Kaapval and Grunneghona Craton which bears strong geochronogical signatures with each other, the extent of Pan-African orogeny, and the Karoo magmatism in Africa and Antarctica.

In fitting India to Antarctica, our model achieves a good alignment of Archean rocks of the Napier Complex and the Eastern Ghat Craton, as well as the alignment of conjugate Gondwanian rifts basins (Mahanadi and Gondavari of India, and Lambert and Enderby rift basin of Antarctica) and Mesoproterozoic rocks between the two plates.

With regard to the fit between Australia and Antarctica, it permits a continuation of the Beardmore and Mawson Cratons in Antarctica into Australia into the Curnamona cratons and Gawler respectively, and continuation of Mesoproretozoic A (1.65-1.55Ga), Mesoproretozoic D (1.35-1.15Ga), Mesoproretozoic E (1.1-1.05Ga), between Antarctica and Australia.

Between Madagascar and India, the 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 (Kuster *et al*., 1990; Lenoir *et al*., 1994 and Tucker *et al*., 2014). It aligns the Precambrian shear zones of the Agavo Ifadiana and Ranostara (Madagascar) to the Palghat and Karrur Kambam shear zones (India), respectively.

Between Africa and Madagascar, we align the Vohibory Pan-African shear zone to the PanAfrican shear zone in Tanzania. The Brava faults in Kenya is fitted to the Andreaparaty shear zone in Madagascar, and the Belet Uen fault in Somalia fitted to the fault lying to the northern border of Madagascar. The Ranotsara shear zone is proposed to continue with the Tombo faults due to their perfect alignment and NW-SW trend, and may continue into Kenya into the Aswa shear zone. The extent of the Neoproterozoic granulites (Napier complex 0.65–0.63 Ga Bingen *et al*., 2009; Tucker *et al*., 2014) in Mozambique and Madagascar is also evident in our model.

9.2 Major conclusions

1. On the question of the role of the Karoo magmatism in the breakup of Gondwana, this work predicts that the Karoo magmatic event did not provide the needed trigger for the breakup of Gondwana.

2. This work predicts that the rifting in Somali and Mozambique Basins rifting may be longer than previously proposed; terminating in the upper Middle Jurrasic and initiating continental breakup onwards.

3. The new model predicts continental origin for the Limpopo Basin and the North Natal Basin, in agreement with the seismic refraction results of Moz3-5 (Lepretre et al., 2017; Verrier et al., 2017), and the magnetic data of Hanyu et al. (2017).

4. The model proposes magnetic anomaly M25 (157Ma) as the oldest magnetic anomaly in the Indian Ocean.

5. The model in agreement with Muller et al., (2016) on the continental origin of the Beira High allows adequate space in the initial fit for its accommodation.

9.3 Outlook

The geochemical analysis of the Karoo volcanism currently being undertaken within the PAMELA Project is crucial to understanding the source of the magma and its role in the evolution of Gondwana. The East Africa margin was subjected to different volcanic episodes whose impact is not adequately answered. The analysis of the volcanics will help us understand their geodynamic context and help answer the lingering questions about their impact on the continental margin.

The conclusions on the wide-angle seismic data in the Limpopo Basin, the North Natal Valley and the North Mozambique Ridge is important for the localization of the continent-oceanboundary in these areas. The question of the nature of the Mozambique and Madagascar Ridges and their transitions to the surrounding basins has not been adequately answered. Further acquisition of field data set; seismic data and systematic sampling of rocks by dredging and drilling could help provide some answers.

The magnetic anomaly identifications of Leinweber *et al*., 2012, in the Central Mozambique near the continental margin was based few data set (2 profiles). Denser data set could help validate or otherwise their identifications, and reveal details about the spreading lineaments in the Mozambique Ocean.

More potential field data set may also be needed in the Somali Basin, the Bay of Bengal, the Enderby Basin, the West Australian Basin, and the Australia-Antarctica Basin to resolve the different interpretations of the spreading anomalies and lineaments in these oceans.

The basement geology of Antarctica is based on aeromagnetic data set of previous studies. Extensive studies may have to be carried out to verify the geometry and extent of the cratons and structures described especially in Boger (2011). Their accurate determination may have implication on the surrounding plates.

Thermal cooling data may be needed to analyse the long-term cooling history of the continental margins.

Modelling for the passive margin within this new setting may be required (as what was done in South Atlantic: Wide-angle and reflection seismic analysis: Contrucci et al., 2004; Moulin et al., 2005, then kinematic analysis: Moulin et al., 2010, Aslanian and Moulin 2012, then passive margins analysis in that setting Aslanian et al., 2009, Aslanian and Moulin 2012, then numerical modelling: Huismans and Beaumont, 2011, 2014).

Passives seismic experiment (tomography) may also be required to have a broad overview of the lithospheric plate (as Rum-Rum and Mozart experiments).

REFERENCES

REFERENCES

Alibert, C., 1991. Mineralogy and geochemistry of a basalt from Site 738: implications for the tectonic history of the southernmost part of the Kerguelen Plateau. Proc. ODP (Ocean Drill. Prog.), Sci. Results, 119: 293-298.

Andrianaivo L. and Ramasiarinoro V.J., 2010: Relation between Regional Lineament Systems and Geological Structures: Implications for Understanding Structural Controls of Geothermal System in the Volcanic Area of Itasy, Central Madagascar. Proceedings World Geothermal Congress 2010, 25-30 April 2010, Bali – Indonesia, Paper 1218, 1-9.

Aslanian D. and Moulin M., 2012. Paleogeographic consequences of conservational models in the South Atlantic Ocean, In: Mohriak, W.U., Danforth, A., Post, P.J., Brown, D.E., Tari, G.C., Nemcok, M. and Sinha, S.T. (Eds). Conjugate Divergent Margins. Geological Society, London, Special Publications, 369, http://dx.doi.org/10.1144/SP369.5.

Aslanian, D., Moulin, M., Olivet, J.-L., Unternehr, P., Matias, L.., Bache, F., Rabineau, M., Nouzé, H., Klingelhoefer, F., Contrucci, I., Labails, C., 2009. Brazilian and African passive margins of the Central Segment of the South Atlantic Ocean: kinematic constraints. Tectonophysics, 468, 98– 112.

Aslanian, D., 1993. Interactionsentreles processus intraplaques et les processusd'accrétionocéanique: l'apport du géoïde altimétrique. These de Doctoratde l'universite de Bretagne Occidentale.

Banks, N.L., Bardwell, K.A. and Musiwa, S., 1995. Karoo Rift Basin of the Luangwa Valley, Zambia. In: J.J. Lambiase (Editor), Hydrocarbon Habitat in Rift Basins. Geological Society, Special Publication, pp. 285-295.

Battail, B., Beltan, L. and Dutuit, J.-M., 1987. Africa and Madagascar during Permo-Triassic time: the evidence of the vertebrate faunas. In: G.D. McKenzie (Editor), Gondwana six: Stratigraphy, Sedimentology, and Paleontology. American Geophysical Union, Geophysical Monograph 41, Washington D.C., pp. 147-155.

Barber, B., 1985. The hydrocarbon potential of the Mid-Zambezi and Save-Limpopo Basins in Zimbabwe. Annals of the Zimbabwe Geological Survey, XI, published 1987: 41-55.

Baby, G., 2017. Mouvements verticaux des marges passives d'Afrique australe depuis 130 Ma, étude couplée : stratigraphie de bassin - analyse des formes du relief. Thèse / Université de Rennes 1, sous le sceau de l'Université Bretagne Loire.

Barrett. P.J., Grindley. G.W. and Wegg, P.N., 1972. The Beacon Supergroup of Hast Antarctica. In; R.J. Adie (F.ditor). Antarctic Geology and Geophysics. Universitetsforlaget. Oslo, pp. 319- 332.

Ben-Avraham, Z., Hartnady, C.J.H. le Roex, A.P., 1995. Neotectonic activity on continental fragments in the Southwest Indian Ocean: Agulhas Plateau and Mozambique Ridge, J. geophys. Res., 100, 6199–6211.Bryan, S.E. & Ernst, R.E., 2008. Revised definition of Large Igneous Provinces (LIPs), Earth-Sci. Rev., 86, 175–202.

Bergh, H.W., 1977. Mesozoic seafloor off Dronning Maud Land, Antarctica. Nature 269, 686–687.

Bernard, A., Munschy, M., Rotstein, Y., Sauter, D., 2005. Refined spreading history at the Southwest Indian Ridge for the last 96 Ma, with the aid of satellite gravity data. Geophysical Journal International 162, 765–778.

Ben-Avraham, Z., Hartnady, C.J.H. and Kitchin, K.A., 1997. Structure and tectonics of the Agulhas-Falkland fracture zone. Tectonophysics, 282, 83–96.

Bernard, A., Munschy, M., Rotstein, Y., Sauter, D., 2005. Refined spreading history at the Southwest Indian Ridge for the last 96 Ma, with the aid of satellite gravity data. Geophysical Journal International 162, 765–778.

Besairie, H., Collignon, M., 1972. Geologie de Madagascar; I, Les terraines sedimentaires. Annales Geol. Madagascar 35, 463.

Bingen B., Jacobs J., Viola G., Henderson I.H.C., Skår Q., Boyd R., Thomas R.J., Solli A., Key R.M., Daudi E.X.F., 2009. Geochronology of the Precambrian crust in the Mozambique belt in NE Mozambique, and implications for Gondwana assembly. Precambrian Research, 170, 231–255.

References

Biswal, T.K. Sinha, S., 2004. Fold-Thrust-Belt Structure of the Proterozoic Eastern Ghats Mobile Belt: A Proposed Correlation Between India and Antarctica in Gondwana. Gondwana Research, I.! 7, No. I, pp. 43-56.

Boger, D.S, 2011. Before and After Gondwana. Gondwana Research 19-335-371.

Bond, G., 1978. Evidence for Late Tertiary uplift of Africa relative to North America, South America, Australia and Europe. Journal of Geology, 86: 47-65.

Bordy, E.M. and Catuneanu, O., 2001. Sedimentology of the upper Karoo fluvial strata in the Tuli Basin, South Africa. Journal of African Earth Sciences, 33: 605-629.

Bordy, E.M., Hancox, P.J. and Rubidge, B.S., 2005. Discussion on 'Basin development during deposition of the Elliot Formation (Late Traissic-Early Jurassic), Karoo Supergroup, South Africa'. South African Journal of Geology, 108: 454-461.

Borg, S.G., DePaolo, D.J., 1991. A tectonic model of the Antarctic Gondwana margin with implications for southeastern Australia: isotopic and geochemical evidence. Tectonophysics, 196 (1991) 339-358.

Borg, S.G., DePaolo, D.J., Smith, B.M., 1990. Isotopic signature and tectonics of the central Transantarctic Mountains. Journal of Geophysical Research 95, 6647 – 6667.

Bond, G., 1973. The palaeontology of Rhodesia. Bull. Rhodesia Geol.Surv. 70, 121.

Bristow. J.W., 1980. The geochronology and geochemistry of Karoo volcanics in the Lebombo and adjacent areas. Department of Geochemistry, University of Cape Town. http://hdl.handle.net/11427/12534.

Bristow. J.W. and Saggerson. K.P., 1983. A general account of Karoo volcanicity in southern Africa. Geol. Rundsch. 72; 1015-1060.

Broderick, T.J., 1981. Coal and coal potential in the MidZambezi valley between Chirundu and Mukumbura. Annals of the Zimbabwe Geological Survey, Vol. 6, 22-26.

Bullard, E.C., Everett, J.E. and Smith, A.G., 1965. A symposium on Continental Drift. IV. The fit of the continents around the Atlantic. Philos. Trans. R. Sot. London, Ser. A, 258; 41-51.

Bunce, E.T. and Molnar, P., 1977. Seismic reflection profiling and basement topography in the Somali Basin; Possible fracture zones between Madagascar and Africa. J. Geo- phys. Res., 82; 5305-5311.

Burke, K. and Dewey, J.F., 1974. Two plates in Africa during the Cretaceous? Nature, 249: 313-316.

Bronner, E.R., 1996. New palynological data from Karoo sediments, Mana Pools basin, northern Zimbabwe. Journal of African Earth Sciences, Vol. 23, No. 1, pp. 17-30, 1996.

Cande, S. C. and Kent, D. V., 1992. A new geomagnetic polarity time scale for the late Cretaceous and Cenozoic.I. Geophys. Res., 97, Bl0: 13917-13951

Cande, S. C. and Mutter, J. C., 1982. A revised identification of the oldest sea-floor spreading anomalies between Ausralia and Antarcaca. Earth Plarct. Sci. Lett. 58: 151-160.

Caress D. W., Menard H. W. and Hey R. N., 1988. Eocene Reorganization of the Pacific-Farallon Spreading Center North of the Mendocino Fracture Zone. J. Geophys. Res., v. 93, p. 2813-2838.

Castelino, J.A., Reichert, C., Klingelhoefer, F., Aslanian, D., Jokat, W., 2015. Mesozoic and Early Cenozoic sediment influx and morphology of the Mozambique Basin. Mar. Pet. Geol. 66, 890–905.http;//dx.doi.org/10.1016/j.marpetgeo.2015.07.028.

Catuneanu, O. and Elango, H.N., 2001. Tectonic control on fluvial styles: the Balfour Formation of the Karoo Basin, South Africa. Sedimentary Geology, 140: 291-313.

Catuneanu, O., 2004. Basement control on flexural profiles and the distribution of foreland facies: The Dwyka Group of the Karoo Basin, South Africa. Geological Society of America June 2004; v. 32; no. 6; p. 517–520; doi: 10.1130/G20526.1.

Catuneanu, O., Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H., Hancox, P.J., 2005. The Karoo basins of south-central Africa. J. Afr. Earth Sci. 43, 211–253

References

Chetty, P., and Green, R. E., 1977. Seismic refraction observations in the Transkei Basin and adjacent areas, Mar. Geophys. Res., 3, 197–208.

Cole, D.I., 1992. Evolution and development of the Karoo Basin. In: M.J. de Wit and I.G.D. Ransome (Editors), Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous basins of Southern Africa. A.A. Balkema, Rotterdam, pp. 87-99.

Collier, J.S., Minshull, T.A., Hammond, J.O.S., Whitmarsh, R.B., Kendall, J.-M., Sansom, V., Lane, C.I., Rumpker, G., 2009. Factors influencing magmatism during continental breakup; new insights from a wide-angle seismic experiment across the conjugate Seychelles–Indian margins. Journal of Geophysical Research 114, 1–25.

Coffin, M.F. and Rabinowitz, P.D., 1987. Reconstruction of Madagascar and Africa: Evidence from the Davie Fracture Zone and western Somali Basin. Journal of Geophysical Research, 92(B9): 9385-9406.

Coffin, M.F. and Rabinowitz, P.D., 1988. Evolution of the conjugate East African-Madagascan margins and the western Somali Basin. Geological Society of America, Special Paper, 226: 1-78.

Colin, J.P. and Jacobs, L., 1990. L'âge des Couches à Dinosaures du Malawi : apport des ostracodes. Comptes Rendus de l'Academie des Sciences, Paris, Série II, 311: 1025-1029.

Reeves, C., De Wit, M., 2000. Making ends meet in Gondwana; retracing the transforms of the Indian Ocean and reconnecting continental shear zones. Terra Nova, 12, 272-280.

Collins, A.S., 2000. The tectonic evolution of Madagascar: its place in the East African Orogen. Gondwana Res. 3, 549–552.

Collins, A.S. and Pisarevsky, S.A., 2005. Amalgamating eastern Gondwana; the evolution of the Circum-Indian Orogens. Earth Science Reviews, 71, 229–270.

Collins, AS., 2006. Madagascar and the amalgamation of central Gondwana. Gondwana Res. 9, 3–16.

Collins, A.S., Windley, B.F., 2002. The tectonic evolution of central and northern Madagascar and its place in the final assembly of Gondwana. J. Geol. 110, 325–339.

Courrier, P. and Lafont, M., 1987. Mise au point sedimento-structurale et petroliere du bassin de morondava.societé nationa!e elf aquitaine (production).

Cox, K.G., 1992. Karoo igneous activity, and the early stages of the break-up of Gondwanaland. In; Storey, B.C., Alabaster, T., Pankhurst, R.J. (Eds.), Magmatism and the causes of continental break-up; Geol. Soc. London Spec. Publ., 68, 137–148.

Cox, G.M., Lewis, C.J., Collins, A.S,, Halverson, G.P., Jourdan, F., Foden, J., Nettle, D., Kattan, F., 2012. Ediacaran terrane accretion within the Arabian–Nubian Shield. Gondwana Research 21-341–352.

Curtis, M. L. and Hyam, D. M., 1998. Late Palaeozoic to Mesozoic structural evolution of the Falkland Islands: a displaced segment of the Cape Fold Belt. Journal of the Geological Society, London, Vol. 155, pp. 115–129.

d'Engelbronner, E.R., 1996. New palynological data from Karoo sediments, Mana Pools basin, northern Zimbabwe. Journal of African Earth Sciences, 23(1): 17-30.

Daly, M.C., Chorowicz, J. and Fairhead, J.D., 1989. Rift basin evolution in Africa: the influence of reactivated steep basement shear zones. In: Inversion tectonics (Edited by Cooper, M.A. and Wiuiams, G.D.), Geological Society London Special Publication, 44, 309-334.

Dalziel, I. W. D., and D. H. Elliot., 1982. West Antarctica; Problem child of Gondwanaland, Tectonics, 1(1), 3–19.

Davis, J.K., Lawver, L.A, Norton, I.O., Gahagan, L.M., 2016. New Somali Basin magnetic anomalies and a plate model for the early Indian Ocean. Gondwana Research 34, 16–28.

Dasgupta, S. Bose, S., Das, K., 2013. Tectonic evolution of the Eastern Ghats Belt, India. Precambrian Research, 227, 247–258.

De Acosta, J., Grimston, E., Markham, C.R., 1880. The Natural and Moral Historie of the Indies, Hakluyt Society, 1880 pp.i-ii

Delvaux, D., 1990. Structural control of the Karoo basins of SW-Tanzania by pre-Karoo fracture pattern. In; Recent data in African Earth Sciences, 15th colloquium of African geology (Edited by Rocci, G. and Deschamps, M.) pp293-296. CIFEG-occasional publication, Nancy, France.

Desa, M., M. V. Ramana, and T. Ramprasad., 2006. Seafloor spreading magnetic anomalies south of Sri Lanka, Mar. Geol., 229, 227–240.

De Waele, B., Fitzsimons, I.C.W., Wingate, M.T.D., Mapani, B.S.E., 2003. The tectonothermal history of the Irumide belt of Zambia. Regional Significance of New Geochronological Constraints, Assembly and Breakup of Rodinia, South China Field Symposium, Hangzhou, China, pp. 16 – 18.

De Wit, M.J., 2003. Madagascar; Heads it's a Continent, Tails It's an Island. Annu. Rev. Earth Planet. Sci. 2003. 31? 213–48.

De Wit, M.J., Bowring, S.A., Ashwal, L.D., Randrianasolo, L.G., Morel, V.P.I., Rambeloson, R.A., 2001. Age and tectonic evolution of Neoproterozoic ductile shear zones in southwestern Madagascar, with implications for Gondwana studies. Tectonics 20 (1), 1–45.

Dietz, R.S., 1961 "Continent and Ocean Basin Evolution by Spreading of the Sea Floor." Nature, 190, 854-516.

Dingle and Scrutton, 1974. Continental breakup and the development of post-Paleozoic sedimentary basins around southern Africa, Geol. Soc. Am. Bull., 85, 1467–1474.

Domingues, A., Silveira, G., Ferreira, A. M.G., Chang, S., Custodio, S., Fonseca, J. F.B.D., 2016. Ambient noise tomography of the East African Rift in Mozambique. Geophys. J. Int, 204, 1565–1578.

Dumoulin, C., M.-P. Doin, and L. Fleitout, 2001. Numerical simulations ofthe cooling of an oceanic lithosphere above a convective mantle, Phys.Earth Planet. Inter., 125, 45 – 64.

Dumoulin, A., Harris, A.G., Blome, D.C., Young, E.L., 2004. Depositional Settings, Correlation, and Age of Carboniferous Rocks in the Western Brooks Range, Alaska. Society of Economic Geologists 361-128. https://doi.org/10.2113/gsecongeo.99.7.1355

Duncan R. A. Clague D. A., 1985. —Pacific plate motion recorded by linear volcanic chains.in: Nairn A. E. M., Stehli F. G., Uyeda S., (eds.). The ocean basins and margins, vol. 7A: The Pacific Ocean, p. 89-121.

Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J.S., Duncan, A.R., 1997. The timing and duration of the Karoo igneous event, southern Gondwana. J. Geophys. Res. 102,18127–18138.http;//dx.doi.org/10.1029/97JB00972.

Duncan, R.A., 2002. A Time Frame for Construction of the Kerguelen Plateau and Broken Ridge. Journal of Petrology 43 (7), 1109–1119.http://dx.doi.org/10.1093/petrology/ 43.7.1109

Du Toit, A.L., 1937. Our Wandering Continents. Oliver and Boyd, Edinburgh, 366 pp. Elliot, D.H., 1975. Tectonics of Antarctica; a review. Am. J. Sci., 275A; 45-106.

Dyment, J., 1991. Structure et, évolution de la lithosphère oceanique dans I'océan Indien : apport des anomalies magnétques. Thèse de Doctorat d'Universit4 Université L-ouis Pasteur, Strasbourg, 374p.

Eagles, G., König, M., 2008. A model of plate kinematics in Gondwana breakup. Geophysical Journal International 173, 703–717.

Elliot, D.H., Fleming, T.H., 2000. Weddell triple junction; the principal focus of Ferrar and Karoo magmatism during initial breakup of Gondwana. Geology 28 (6), 539–542.

Elliot, D.H., Fleming, T.H., 2004. Occurrence and dispersal of magmas in the Jurassic Ferrar Large Igneous Province, Antarctica. Gondwana Research 7, 223–237.

Eriksson, P.G., 1985. The depositinal palaeoenvironment of the Elliot Formation in the Natal Drakensberg and North-Eastern Orange free State. Transactions of the Geological Society of South Africa, 88: 19-26.

Argand, E. 1911d: Sur la tectonique de la grande zone permo-houillere des Alpes occidentales. Eclogae geol. Helv. 11, 747-751 et Actes Soc. helv. Sci. nat. 94me session, Soleure, Bd. 1,265-266.

References

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

Faure, K., Armstrong, R. A., Willis, J., 1996. Provenance of mudstones in the Karoo Supergroup of the Ellisras basin, South Africa: geochemical evidence. Journal of African Earth Sciences. Vol. 23, No. 2, PP.

189.204.

Findlay, U. R., Banks, M.R. and Veevers, J.J., 1991. Gondwana Eight: Assembly, evolution and dispersal: Proceedings of the Gondwana symposium, Hobart, Tasmania, Australia.

Fitzsimons, I.C.W., 2000. Grenville-age basement provinces in East Antarctica: Evidence for three separate collisional orogens. Tectonics Special Research Centre, School of Applied Geology, Curtin University of Technology Australia.

Flores, G. Barbieri, F., 1959. Outline of the stratigraphy of Mozambique between the Maputo and Zambezi rivers. Unpub. Info, available in SECH archives, Maputo.

Flores, G., 1964. On the age of the Lupata rocks, lower Zambezi River, Mozambique. Trans. Geol. Soc. S. Afr. 67 p1ll—118.

Flores, G., 1970. Suggested origin of the Mozambique Channel. Trans. Geol. Soc. South Afr.

Flores, G., 1973. The Cretaceous and Tertiary basins of Mozambique and Zululand. Ass. Afr. Geol. Surveys in Symp of East Afr. Coast. Basins Paris..

Francis, T.J.G., Shor G., 1966. Seismic refrac- tion measurements in the northwest Indian Ocean, J. Geophys. Res., 71, 427-449.

Forster, R., 1975. The geological history of the sedimentary basin of Southern Mozambique, and some aspects of the origin of the Mozambique Channel. Palaeogeography, Palaeoclimatology, Palaeoecology 17, 267–287

Franzese J, Martino R., 1998. Aspectos cinemáticos y tectónicos de la zona de cizalla de Gastre en la Sierra de Calcatapul, Provincia de Chubut; Argentina. In: X Congreso Latinoamericano de Geología y VI Congreso Nacional de Geología Económica (Buenos Aires), Actas II, 3.

Frey, F.A., Coffin, M.F., Wallace, P.J., Weis, D., Zhao, X., Wise Jr., S.W., ... Antretter, M., 2000. Origin and evolution of a submarine large igneous province: the Kerguelen Plateau and Broken Ridge, southern Indian Ocean. Earth and Planetary Science Letters 176 (1), 73–89. http://dx.doi.org/10.1016/S0012-821X(99)00315-5.

Fullerton, L. G., Sager, andHandschumacher, I..W., 1989. Late Jurassic-Early Cretaceous evolution of the Eastem Indian ocean adjacent to Northwest Australia. J. Geophys. Res., 94, 83:2937-2953.

Gaina, C., Müller, R.D. Brown, B. and Ishihara, T., 2007. Breakup and early seafloor spreading between India and Antarctica, Geophys. J. Int., 170, 151–169, doi;10.1111/j.1365-246X.2007.03450.x.

Gaina, C., Torsvik, T., Van Hinsbergen, D., Medvedev, S., Werner, S. and Labails, C., 2013. The African Plate; A history of oceanic crust accretion and subduction since the Jurassic. Tectonophysics, doi; 10.1016/j.tecto.2013.05.037

Gaina, C., van Hinsbergen, D. J.J. andSpakman, W., 2015. Tectonic interactions between India and 248 Arabia since the Jurassic reconstructed from marine geophysics, ophiolite geology, and seismic 249 tomography. Tectonics, 34, 875–906. doi:10.1002/2014TC003780.

Gaina, C., van Hinsbergen, D.J.J. and Spakman, W., 2015. Tectonic interactions between India and Arabia since the Jurassic reconstructed from marine geophysics, ophiolite geology, and seismic tomography. Tectonics, 34, 875–906. Doi;10.1002/2014TC003780.

Geiger, M., Clark, D.N. and Mette, W., 2004. Reappraisal of the timing of the breakup of Gondwana based on sedimentological and seismic evidence from the Morondava Basin, Madagascar. Journal of African Earth Sciences, 38: 363-381.

Georgen, J. E., 2008, Mantle flow and melting beneath oceanic ridge-ridge-ridge triple junctions, Earth Planet. Sci. Lett., 270, 231–240.

Ghosh, J.G., De Wit, M.J., Zartman, R.E., 2004. Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite Terrain of India, with implications for Gondwana studies. Tectonics, VOL. 23, TC3006, doi;10.1029/2002TC001444, 2004.

Gibbons, A. D., J. M. Whittaker, and Müller, R. D., 2013. The breakup of East Gondwana: Assimilating 245 constraints from Cretaceous ocean basins around India into a best-fit tectonic model, J. Geophys. Res. Solid 246 Earth, 118, 808–822, doi:10.1002/jgrb.50079.

Gnos, E., Immenhauser, A., Peters, T., 1997. Late Cretaceous/early Tertiary convergence between the Indian and Arabian plates recorded in ophiolites and related sediments. Tectonophysics, 271, 1-19.

Gohl, K. and Uenzelmann-Neben, G., 2001. The crustal role of the Agul-has Plateau, southwest Indian Ocean: evidence from seismic profiling, Geophys. J. Int.,144, 632–646

Gohl, K., Uenzelmann-Neben, G., Grobys, N., 2011. Growth and dispersal of a Southeast African large igneous province. S. Afr. J. Geol. 114, 379–386.http;//dx.doi.org/10.2113/gssajg.114.3-4.379.

González, L., F., 2001. La cinématique de l'Atlantique Nord : la question de la déformation intraplaque. These de Doctoratde l'universite de Bretagne Occidentale. Volume 1.

Goodlad, S.W., Martin, A.K., Hartnady, C.J.H., 1982. Mesozoic magnetic anomalies in the southern Natal Valley. Nature 295, 686–688.http;//dx.doi.org/10.1038/295686a0.

Gosena, V., Loske, W., 2004. Tectonic history of the Calcatapul Formation, Chubut province, Argentina, and the "Gastre fault system". Journal of South American Earth Sciences 18 , 73–88.

Goslin. J., 1981. Etude geophysique des reliefs asismiques de l'Ocean Indien occidental et austral, Thése d'Etat, UniversitC Louis-Pasteur. Strashourg, 267 pp.

Goslin. J. and Patriat. P., 1984. .Ahsolute and relative plate motions and hypotheses on the origin of five aseismic ridges in the Indian Ocean. Tectonophysics. 101: 221.-244.

Goslin. .I. and Schlich, R., 1982. Structural limits of the xx~thern C'rozet Basin and its relation to the Enderby Basin and the Kergueten-bfeard Plateau. In: C'. (Craddock (Editor). Antarctic Geology and Geophysics. The University of Wisonsin Press, Madkhon. WISC. I172 pp.

Green, A.G., 1972. Seafloor spreading in the Mozambique Channel Nature, 236, l9-21.

Gueodekian, A.A. et al. 1984. The composition and occurrence of hydrocarbon bearing formation in the sedimentary basins of Mozambique. Geological Proceedings, 3, l24-133.

Green, D., Crockett, R.N. and Jones, M.T., 1980. Tectonic Control of Karoo sedimentation in Mid-Eastern Botswana. Transactions of the Geological Society of South Africa, 83, 213-219.

Gradstein, F.M., Ogg, J.G., Smith, A.G., 2004. A Geologic Time Scale 2004. Cambridge University Press, Cambridge. 589 p.

Grantham, G.H., Macey, P.H.,Ingram, B.A.,Roberts,M.P.,Armstrong, R.A.,Hokada,T., Shiraishi, K., Jackson, C., Bisnath, A., Manhica, V., 2008. Terrane correlation between Antarctica, Mozambique and Sri Lanka; comparisons of geochronology, lithology, structure and metamorphism and possible implications for the geology of southern Africa and Antarctica, in; Geodynamic Evolution of East Antarctica; A Key to the East–West Gondwana Connection. In; Satish-Kumar, M., Motoyoshi, Y., Osanai,Y.,Hiroi,Y.,Shiraishi,K.(Eds.),GeologicalSociety.SpecialPublication 308, 91–119 London.

Greenway, M.E., 1972. Geology of the Falkland Islands. Department of geology, University of Birmingham.

Grégoire M., Lorand J. P., Cottin J.-Y., Giret A., Mattielli N., Weis D., 1997. Petrology of Kerguelen mantle xenoliths: evidence of a strongly refractory oceanic mantle percolated by basaltic melts. European Journal of Mineralogy, 9, 1085-1100.

Guiraud, R., Bosworth, W., Thierry, J., Delplanque, A., 2005. Phanerozoic geological evolution of Northern and Central Africa; An overview. Journal of African Earth Sciences 43, 83–143.

Hankel, O., 1987. Lithostratigraphic subdivision of the Karoo rocks of the Luwegu Basin (Tanzania) and their biostratigraphic classification based on microfloras, macrofloras, fossils woods and vertebrates. Geologische Rundschau, 76, 539-565.

Hastie, W.W., Watkeys, M.K. and Aubourg, C., 2014. Magma flow in dyke swarms of the Karoo LIP; implications for the mantle plume hypothesis. Gondwana Research, 25, 736–755.

Hayes. D.E. and Rmgis. J., 1973. Seafloor spreading in the Tasman Sea. Nature. 243: 454--45.

Heezen, B.C., and M. Tharp., 1965. Physiographic Diagram of the Indian Ocean the Red Sea the South China Sea the Sulu Sea and the Celebes Sea, Geological Society of America, New York, 1965.

Heirtzler, T.R. and Burroughs, R.W., 1971. Madagascar's palaeo-position. New data from the Mozambique Channel. Science 174, 488-490.

Hess, H.H., 1962 "History of Ocean Basins. Pterological Studies; A Volume in Honor of AF Buddington." AEJ Engel, et al 599.

Hey R. N., Menard H. W., Atwater T. M. and Caress D. W., 1988. Changes in direction of seafloor spreading revisited. J. Geophys. Res., 93, 2803-2811.

Hiller, K., and Shoko, U., 1996. Hydrocarbon source rock potential of the Karoo in Zimbabwe. Journal of African Earth Sciences, 23, 31-43.

Himmler, T., Freiwald, A., Stollhofen, H. and Peckmann, J., 2008. Late Carboniferous hydrocarbon-seep carbonates from the glaciomarine Dwyka Group, southern Namibia. Palaeogeography, Palaeoclimatology, Palaeoecology, 257(12): 185-197.

Hinz, K., Krause, W., 1982. The continental margin of Queen Maud Land, Antarctica; seismic sequences, structural elements and geological development. Geologisches Jahrbuch, Reihe E 23, 17–41.

Hinz, K., Neben, S., Gouseva, Y.B., Kudryavtsev, G.A., 2004. A compilation of geophysical data from the Lazarev Sea and the Riiser-Larsen Sea, Antarctica. Marine Geophysi-cal Research 25, 233–245.

Hirsch, F., 1987. The Gondwanian Triassic and Jurassic Tethys shelf: Sephardic and Ethiopian faunal realms. In: K.G. McKenzie (Editor), Shallow Tethys 2, Proceedings of the International Symposium on Shallow Tethys 2, Wagga Wagga. A.A.Balkema, Rotterdam, pp. 215-232.

Eagles, E., Hoang, H., 2013. Cretaceous to present kinematics of the Indian, African and Seychelles plates. Geophysical Journal International, Volume 196, Issue 1, 1 January 2014, Pages 1–14.

Holmes, A., 1944. Principles of Physical Geology. Nelson, London, 532 pp.

Holzförster, F., Stollhofen, H. and Stanistreet, I.G., 1999. Lithostratigraphy and depositional environments in the Waterberg-Erongo area, central Namibia, and correlation with the main Karoo Basin, South Africa. Journal of African Earth Sciences, 29: 105-123.

Jacobs, J., Fanning, C.M., Henjes-Kunst, F., Olesch, M., Paech, H., 1998. Continuation of the Mozambique Belt into East Antarctica: Grenville-age metamorphism and polyphase Pan-African high-grade events in central Dronning Maud Land. Journal of Geology 106, 385–406.

Jacobs, J., Pisarevsky, S., Thomas, R.J., Becker, T., 2008. The Kalahari Craton during the assembly and dispersal of Rodinia. Precambrian Research 160, 142–158.

Jacobs, J., Bauer, W., Fanning, C.M., 2003a. Late Neoproterozoic/Early Palaeozoic events in central Dronning Maud Land and significance for the southern extension of the East African Orogen into East Antarctica. Precambrian Research 126, 27–53.

Jacobs, J., Thomas, R.J., 2004. Himalayan-type indenter-escape tectonics model for the southern part of the Neoproterozoic–early Paleozoic East African–Antarctic orogen. Geology 32, 721–724.

Jaeger, J. J., Courtillot, V. and Tapponnier, P., 1989. Paleontological view of the ages of the DeccanEâps, the CretaceousÆertiary boundary, ând ttre India-Asia collision. Earth Planet. Sci. Lett. 17: 316319

Jokat, W., Boebel, T., König, M., Meyer, U., 2003. Timing and geometry of the early Gondwana breakup. Journal of Geophysical Research 108 (B9), 1–15.

Jokat, W., Nogi, Y., Leinweber, V., 2010. New aeromagnetic data from the western Enderby Basin and consequences for Antarctic–India break-up. Geophysical Re-search Letters 37 (L21311).

Johns, C.C., 1986. Karoo stratigraphy in part of western Zambia; results of a reconnaissance coal exploration programme. Geological Survey Department, Republic of Zambia, Technical Report, 101: 22 p.

Johns, C.C., 1986. An outline of the geology of the Luangwa area. Geological Survey Department, Republic of Zambia, Technical Report, 98: 12 p.

Jourdan, F. et al., 2005. Karoo large igneous province: Brevity, origin, and relation to mass extinction questioned by new 40Ar/39Ar age data. Geology, 33: 745-748. Jourdan, F. et al., 2006. Basement control on dyke distribution in Large Igneous Provinces: Case study of the Karoo triple junction. Earth and Planetary Science Letters, 241: 307-322.

Jourdan, F., Féraud, G., Bertrand, H., Watkeys, M.K. and Renne, P.R., 2007. Distinct brief major events in the Karoo large igneous province clarified by new 40Ar/39Ar ages on the Lesotho basalts. Lithos, 98: 195-209.

Jourdan, F., Féraud, G., Bertrand, H., Kampunzu, A.B., Tshoso, G., Watkeys, M.K., Le Gall, B., 2005. Karoo large igneous province; brevity, origin, and relation to mass extinction questioned by new 40Ar/39Ar age data. Geology 33, 745–748.

Kazmin, V.G., 1991. Collision and rifting in the history of the Tethys Ocean. Geotektonika, 5, 14-23. Tectonophysics, 196, 371-384.

Kaaya, C.Z., 1992. Depositional environment of late Permian Karoo Beds in the Ruhuhu Basin and Mikumi Area of Tanzania. Geologisches Institut der Universitaet zu Koeln Sonderveroeffentlichungen, 83: 121 p.

Klausen, M.B., 2009. The Lebombo monocline and associated feeder dyke swarm; diag-nostic of a successful and highly volcanic rifted margin? Tectonophysics 268, 42–62.

Kejato, Kejo, 2003, The geology and petroleum potential of Tanzania: Dar es Salaam, Tanzania, Tanzania Petroleum Development Corporation, 29 p.

Kelly, N.M., Clarke, G.L., Fanning, C.M., 2002. A two-stage evolution of the Neoproterozoic Rayner Structural Episode; new U–Pb sensitive high resolution ion microprobe constraints from the Oygarden Group, Kemp Land, East Antarctica. Precambrian Research 116, 307–330.

Klimke, J., Franke, D., 2016. Gondwana breakup: no evidence for a Davie Fracture Zone offshore northern Mozambique, Tanzania and Kenya. Terra Nova, 28, 4, 233–244.

Ketchum, H.F., Barrett, P.M., 2004. New reptile material from the Lower Triassic of Madagascar: implications for the Permian-Triassic extinction event. Can. J. Earth Sci. 41, 1–8.

Key, R.M. et al., 2008. Revised lithostratigraphy of the Mesozoic-Cenozoic succession of the onshore Rovuma Basin, northern coastal Mozambique. South African Journal of Geology, 111: 89-108.

König, M., Jokat, W., 2006. The Mesozoic breakup of the Weddell Sea. Journal of Geophysical Research, 111, B12102, doi:10.1029/2005JB004035.

König, M., Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potentialfield data. Geophysical Journal International 180 (1), 158–180.

Kreuser, T., Schramedei, R. and Rullkötter, J., 1988. Gas-Prone source rocks from Cratogene Karoo Basins in Tanzania. Journal of Petroleum Geology, 11(2): 169-184.

Kreuser, T. and Semkiwa, P.Z., 1987. Geometry and depositional history of a Karoo (Permian) Coal Basin (Mchuchuma'Ketewaka) in SW-Tanzania. Neves Jahrbuch für Geologie und Paläontologie, 2: 69-98.

Kreuser, T. et al., 1990. Depositional evolution of Permo-Triassic Karoo basins in Tanzania with reference to their economic.

Kuster, D., Utke, A., Leupolt, L., Lenoir, J.L., Haider, A., 1990. Pan-African granitoid magmatism in northeastern and southern Somalia. Berliner Geowissenschaftliche Abhandlungen 120, 519 – 536.

Labails, C., Olivet, J.L., Aslanian, D. & Roest, W.R., 2010. An alternative early opening scenario for the Central Atlantic Ocean, Earth planet. Earth and Planetary Science Letters 297 (2010) 355–368.

Lafourcade, 1984. Etude géologique et géophysique de la marge continentale au Sud de Mozambique (17°S à 28°S). (Thèse 3ème cycle) Université P. et M. Curie, Paris.

Lawver, L.A. et al., 1985. Mesozoic and Cenozoic reconstructions of the South Atlantic. Tectonophysics (in press) Proc. IUGG Symposium of Geophysics of Polar Regions XVIII Assembly - Hamburg, Germay 12-27 August 1983.

Leinweber, V.T., Jokat, W., 2011. Is there continental crust underneath the Northern Natal Valley and the Mozambique Coastal Plains. Geophysical Research Letters 38, L14303.

Leinweber, V.T., 2011. Geophysical study of the conjugate East African and East Antarctic margins. vorgelegt dem Fachbereich Geowissenschaften der Universität Bremen. l'École Doctorale des Sciences de la Mer der Université de Bretagne Occidentale Brest.

Leinweber, V., Klingelhoefer, F., Neben, S., Reichert, C., Aslanian, D., Matias, L., Heyde, I., Schreckenberger, B. and Jokat, W., 2013. The crustal structure of the central Mozambique continental margin —wide-angle seismic, gravity and magnetic study in the Mozambique Channel, Eastern Africa. Tectonophysics 599, 170-196.

Leinweber, V.T., Jokat, W., 2012. The Jurassic history of the Africa-Antarctica corridor—new constraints from magnetic data on the conjugate continental margins. Tectonophysics, 530-531, 87–101. http://dx.doi.org/10.1016/j.tecto.2011.11.008.

Leitchenkov, G.L., et al., 2014.Structure of the Earth's crust and tectonic evolution history of the Southern Indian Ocean (Antarctica). Geotectonics 48 (1), 5–23.

Lenoir, J.L., Légois, J.P., Theuninissen, K., Klerkx, J., 1994. The Palaeoproterozoic Ubendian shear belt in Tanzania; geochronology and structure. Journal of African Earth Sciences, Vol. 19, No. 3, pp. 169-184, 1994.

Le Gall, B. et al., 2005. The Okavongo giant mafic dyke swarm (NE Botswana): its structural significance within the Karoo Large Igneous Province. Earth and Planetary Science Letters, 27: 2234-2255.

Leprêtre, A., Fanny, V., Evain, M., Schnurle, P., Watremez, L,Aslanian, D., De Clarens, P., Afonso, N., Afilhado, A. Leroy, d'Acremont, E,, Castilla, R., Moulin, M., 2017. First results on the crustal structure of the Natal Valley from combined wide-angle and reflection seismic data (MOZ3/5 cruise), South Mozambique Margin.. EGU Poster.

Le Pichon, X., Sea floor spreading and continental drift, J. Geophys. Res., 73, 3661-3697, 1968.

Livermore, R.A., Hunter, J., 1996. Mesozoic seafloor spreading in the southern Weddell Sea, in Weddell Sea Tectonics and Gondwana Break up. In; Storey, B.C., King, E.C.,Livermore, R.A. (Eds.), Geol. Soc. Spec. Publ., 108, pp. 227–241.

Lock, B.E., 1978. The Cape Fold Belt of South Africa; tectonic control of sedimentation. Proc. Geol. Ass., 89(1), 263-281.

Lonsdale P., 1988. Geography and History of the Louisville Hotspot Chain in the Southwest Pacific. J. Geophys. Res., 93, p. 3078-3104.

Lorenzo, J.M., Mutter, J.C., 1988. Seismic stratigraphy and tectonic evolution of the Falkland/Malvinas Plateau. Lamont-Doherty Geological Observatory of Columbia University. Palisades, New York 10964-0190, U.S.A.

Mahanjane, E.S., 2012. A geotectonic history of the northern Mozambique Basin including the Beira High—A contribution for the understanding of its development. Mar. Pet. Geol. 36, 1–12.http;//dx.doi.org/10.1016/j.marpetgeo.2012.05.007.

Mark, K.M. and Tikku, A.A., 2001. Cretaceous reconstructions of East Antarctica, Africa and Madagascar. Earth and Planetary Science Letters 186, 479-495

References

Martin, A.K., Hartnady, C. J. H., 1986. Plate tectonic development of the South West Indi-an Ocean; a revised reconstruction of East Antarctica and Africa. Journal of Geo-physical Research 91 (B5), 4767–4786.

Martin, A.K., Goodlad, S.W., Hartnady, C. J. H., Du Plessis, A., 1982. Cretaceous palaeo-positions of the Falkland Plateau relative to southern Africa using Mesozoic seafloor spreading anomalies. Geophysical Journal of the Royal Astronomical Society 71, 567–579.

Marshall, J.E., 1994. The Falkland Islands; a key element in Gondwana paleogeography. Tectonophysics, 13, 499–514.

McElhinny, M.W., Embleton, B.J.J., Daly, L. and Pozzi, J.P., 1976. Paleomagnetic evidence for the location of Madagascar in Gondwanaland. Geology, 4; 455-457.

McKenzie, D., Sclater, J.G, 1971. The Evolution of the Indian Ocean since the Late Cretaceous. Geophys. J. R. usfr. Soc. 25, 437-528.

McMillan, I.K., Brink, G.J., Broad, D.S. and Maier, J.J., 1997. Late Mesozoic sedimentary basins off the south coast of South Africa. In: R.C. Selley (Editor), African basins. Sedimentary basins of the world. Elsevier, Amsterdam, 319-376.

Mbede, E.I., 1987. A review of the hydrocarbon potential of Kenya. Journal of African Earth Sciences, 6: 313-322. McMillan, I.K., 2003. Foraminiferally defined biostratigraphic episodes and sedimentation pattern of the Cretaceous drift succession (Early Barremian to Late Maastrichtian) in seven basins on the South African and southern Namibian continental margin. South African Journal of Science, 99, 537-576.

Melluso, L., Cucciniello, C., Petrone, C.M., Lustrino, M., Morra, V., Tiepolo, M., Vasconcelos, L., 2008. Petrology of Karoo volcanic rocks in the southern Lebombo monocline, Mozambique. J. African Earth Sci. 52, 139–151.

Mitchum, R.M., Vail, P.R., Thompson, S., 1977. Seismic Stratigraphy and Global Changes of Sea Level, Part 2: The Depositional Sequence as a Basic Unit for Stratigraphic Analysis, in: Payton, C.E. (Ed.), Seismic Stratigraphy: Applications to Hydrocarbon Exploration American Association of Petroleum Geologists Memoir 26. 53–62.

Mougenot, D., Gennesseaux, M., Hernandez, J., Lepvrier, C., Malod, J.A., Raillard, S., Vanney, J.R. & Villeneuve, M., 1991. The Mozambique Ridge (Indian-Ocean)—a continental fragment shaped during the transform motion of American and Antarctic plates along East-Africa, C. R. Acad. Sci., Paris II, 312, 655–662.

Money, N.J., 1972. An outline of the geology of Western Zambia. In: A.R. Drysdall, R.L. Johnson and M. Kershaw (Editors), Records of the Geological Survey, Republic of Zambia. Ministry of Mines and Mining development, Lusaka, Republic of Zambia, 103-123.

Moulin, M., 2003. Etude géologique et géophysique des marges continentales passives:exemple du Zaïre et de l'Angola, Ph. D Thesis, Univ de Bretagne Occidentale, Brest, 2, 32. http://www.ifremer.fr/docelec/doc/2003/these-82.pdf.

Moulin, M. andAslanian, D., 2010. Corrigendum to 'A new starting point for the South and Equatorial Atlantic Ocean' [Earth Science Reviews 98 (2010), 1–37]. Earth Science Reviews, 103, 197–198, doi: 267 10.1016/ j.earscirev.2010.10.001

Moulin, M., Aslanian, D., Olivet, J-L., Contrucci, I., Matias, L., Géli, L., Klingelhoeffer, F., Nouzé, H., Réhault, J.-P., Unternehr, P., 2005. Geological constraints on the evolution of the angolan margin based on reflection and refraction seismic data ZaïAngo project. Geophysical Journal International 162, 793–810.

Moulin, M., Aslanian, D., Unternehr, P., 2010. A new starting point for the South and Equatorial Atlantic Ocean. Earth-Science Reviews, 98, 1–37.

Moulin, M., Aslanian, D., 2016a. PAMELA-MOZ03 cruise, RV Pourquoi pas ?, http://dx.doi.org/10.17600/16001600.

Moulin, M., Aslanian, D., 2016b. PAMELA-MOZ03 cruise, RV Pourquoi pas ?, http://dx.doi.org/10.17600/16009500.

References

Moulin, M., Aslanian, D., Evain, M., 2016. Rapport d'information de la campagne pamela-moz 3/5. PAMELAMOZ03/5 cruise, RV Pourquoi pas ?

Moulin, M., Aslanian, D., Evain, M., Thompson, J., Leprêtre, A., Loureiro, A., Dias, N., Schnurle, P., De Clarens, P., Picot, M., Davy, C., Crozon, J., Fernagu, P., Roudaut, M., Corela, C., Duarte, J.L., Inguane, H., Senkans, A., Afilhado, A., Leroy, S., Droz, L., D'acremont, E., Bronner, A., Castilla, R., Le Boutellier, P., Moocroft, D., Fischer, M., Franke, D., Rombe, C., Mahanjane, S., Apprioul, R., Ferrant, A., Le Bihan, C., Pelleau, P., Pierre, D., Pitel1, M., The Gondwana breakup and evolution: insigths from the Northern Natal Valley (submited to Nature Geosciences).

Morgan, J.V., Barton, P.J., White, R.S., 1989. TheHatton Bank continental margin—III. Struc-ture from wideangle OBS and multichannel seismic refraction profiles. Geophysical Journal International 98, 367–384.

Mougenot, D., Virlogeux, P., Vanney, J.R., Malod, J.A., 1986. La marge continentale au Nord du Mozambique; résultats préliminaires de la campagne MD40/MACAMO. Bulletin de la Societe Geologique de France 2 (3), 419–422.

Mueller, C.O., Jokat, W. and Schreckenberger, B., 2016. The crustal structure of Beira High, central Mozambique—Combined investigation of wide-angle seismic and potential field data. Tectonophysics, 683,233254.

Muller, R.D., Roest, W. R., Royer, J.Y., Gahagan, L.M .and Sclater, J.G., 1997. Digital isochrons of the world's ocean floor, J. Geophys. Res., 102, 3211– 3214.

Muller, R.D., Gaina, C., Tikku, A.A., Mihut, D., Cande, S.C. and Stock, J.M., 2000. Mesozoic / Cenozoic tectonic events around Australia, in The History and Dynamics of Global Plate Motions,pp.161–188,eds Richards, M.A., Gordon, R. and van der Hilst, R., AGU Geophysical Monograph.

Muller, R.D., Sdrolias, M., Gaina, C. and Roest, W. R. 2008. Age, spreading rates, and spreading asymmetry of the world's ocean crust. Geochemistry, Geophysics, Geosystems, 9, 1–19.

Mutter, J.C., Buck, W.R., Zehnder, C.M., 1988. Convective partial melting; 1. A model for the formation of thick basaltic sequences during the initiation of spreading. Journal of Geophysical Research 93 (B2), 1031–1048.

Mutterlose, J., Wise, S. W., 1990. Lower Cretaceous nannofossil biostratigraphy of ODP Leg 113 Holes 692B and 693A, continental slope off East Antarctica, Weddell Sea, Proc. Ocean Drill. Program Initial Rep., 113, 325–352.

Nakanishi, M., and Winterer, E.L., 1998, Tectonic history of the Pacific-Farallon-Phoenix triple junction from Late Jurassic to Early Cretaceous: An abandoned Mesozoic spreading system in the central Pacific Basin: Journal of Geophysical Research, 103, 12 453–12 468.

Nguyen, L.C., Hall, S.A., Bird, D.E., Ball, P.J., 2016. Reconstruction of the East Africa and Antarctica continental margins. J. Geophys. Res. Solid Earth 121, 4156–4179. doi:10.1002/2015JB012776.

Nessen, G., Petitperrin, B., Chanut, C., 1988 Bilan petrolier du bassin de Morondava. Societé Nationa!e Elf aquitaine (production).

Nicholas, C.J. et al., 2006. Stratigraphy and sedimentology of the Upper Cretaceous to Paleogene Kilwa Group, southern coastal Tanzania. Journal of African Earth Sciences, 45: 431-466.

Norton, I.O., Sclater, J.G., 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. Journal of Geophysical Research 84 (B12), 6803–6830.

Oesterlen, P.M. and Lepper, J., 2005. The Lower Karoo coal (k23) of the Mid-Zambezi basin, Zimbabwe: depositional analysis, coal genesis and palaeogeographic implications. International Journal of Coal Geology, 61(1-2): 97-118.

Olivet J. L. (1978). —Un nouveau modèle d'évolution de l'Atlantique Nord et Central.— Thèse d'État.Univ. Paris VII.

Olivet J. L., Bonnin J., Beuzart P. et Auzende J. M., 1984. —Cinématique de l'Atlantique Nord et Central.— Rapp. Sci. Tech. C.N.E.X.O., v. 54, 108 p.

Olivet, J.-L., 1996. Kinematics of the Iberian plate. Bull. S.N.Elf Aquitaine Production, F-64018 Pau.

Ortelius, A., 1596, Thesaurus Geographicus (in Latin) (3 ed.), Antwerp; Plantin, OCLC 214324616 (First edition published 1570, 1587 edition online)

Orpen, J.L., Swain, C.J., Nugent, C. and Zhou, P.P., 1989. Wrench-fault and half-graben tectonics in the development of the Palaeozoic Zambezi Karoo Basins in Zimbabwe - the "Lower Zambezi" and "Mid-Zambezi" basins respectively - and regional implications. Journal of African EarthSciences, 8(2/3/4): 215-229.

Pa´lfy, J., and Smith, P.L., 2000, Synchrony between Early Jurassic extinction, oceanic anoxic event, and the Karoo-Ferrar flood basalt volcanism: Geology, 28, 747–750, doi: 10.1130/0091-7613028,0747:SBEJEO.2.3.CO;2.

Pellen, R., 2016. Géodynamique et impact de la crise d'érosion et de salinité Messinienne sur les transferts sédimentaires (bassins de Valence et Adriatique) par Romain. These de Doctoratde l'universite de Bretagne Occidentale.

Pique, A., Laville, E., Bignot, G., Rabarimanana, M. and Thouin, C., 1999. L'ouverture et le developpement du bassin de Morondava (Madagascar) du Carbonifere superieur au Jurassique moyen. Donnees stratigraphiques, sedimentaires, paleontologiques et structuralesThe initiation and development of the Morondava Basin Madagascar from the Late Carboniferous to the Middle Jurassic: sedimentary, palaeontological and structural data. Journal of African Earth Sciences, 28(4): 931-948.

Patriat, P., Parson, L., 1989. A survey of Indian Ocean niple junction trace within ttre Antarctic Plate.Implications for ttre junction evolution since 15 Ma. Mar. Geophys.Res. ll: 89-100.

Patriat, P., Schlich, R., non publié. A Paleocene fossil ridge in the Mascarene basin : implications for the relations between lvladagascar, Seychelles and India.

Patriat, P., Ségoufin, J., 1988. Reconstruction of the Central Indian Ocean. In: Scotese, C. R. &Sager, W. W. (eds.); Mesozoic and Cenozoicplaæ Reconstructions. Elsevier Sci. Pub., Amsærdam, 2ll-234.

Patriat, P., Ségoufin, J., Goslin, J. and Beuzart, P., 1985. Relative positions of Africa and Antarctica inthe Upper Cretaceous : evidence for a non-stationary behaviour of fracture zones. Earth Planet. Sci. Lett. 75, 211-214.

Patriat, P., Ségoufin, J., Schlich, R., Goslin, J., Auzende, J. M., Beuzart, P., Bonnin, J. and Olivet, J.L., 1982. Les mouvements relatives de I'Inde, de I'Afrique et de I'Eurasie. Bull. Soc. Géol. France,t. XXIV, no 2:363-373.

Pellen, R., 2016. Géodynamique et impact de la crise d'érosion et de salinité Messinienne sur les transferts sédimentaires (bassins de Valence et Adriatique) par Romain. These de Doctoratde l'universite de Bretagne Occidentale.

Pique, A., Laville, E., Bignot, G., Rabarimanana, M. and Thouin, C., 1999. L'ouverture et le developpement du bassin de Morondava (Madagascar) du Carbonifere superieur au Jurassique moyen. Donnees stratigraphiques, sedimentaires, paleontologiques et structuralesThe initiation and development of the Morondava Basin Madagascar from the Late Carboniferous to the Middle Jurassic: sedimentary, palaeontological and structural data. Journal of African Earth Sciences, 28(4): 931-948.

Charvis, P., Recq, M., Operto, S., Brefort, D., 1995. Deep structure of the northern Kerguelen Plateau and hotspot-related activity. Journal of Geophysical Science. Volume 122, Issue 3 December 1995 Pages 899–924

Powell, C., Johnson, B.D., Veevers, J. J., 1980. A revised fit of east and west Gondwanaland. Tectonophysics, 63, 13-29.

Quennell, A.M., McKinlay, A.C.M., Aitken, W.G., 1956. Summary of the geology of Tanganyika, Part I: Introduction and stratigraphy. Geological Survey of Tanganyika, Memoir 1, 264 pp

Rabinowitz, P.D., Coffin, M.F., Falvey, D., 1983. The separation of Madagascar and Africa. Science 220, 67–69.

Raillard, S., 1990. Les marges de l'Afrique de l'Est et les zones de fracture associées; Chaine Davie et Ride du Mozambique, Ph.D. thesis, Laboratoire de Géodynamique sous-marine Villefranche-sur-mer et Département de Géologie Océanique Paris, Université Pierre et Marie Curie.

Rakotosolofo, N.A., Torsvik, T.H., Ashwal, L.D., Eide, E.A. and de Wit, M.C., 1999. The Karoo Supergroup revisited and Madagascar-Africa fits. Journal of African Earth Sciences, 29: 135-151.

Rakotosolofo, N.A ., Torsvik, T.H., Ashwal, I.D., Eide, E.A., De Wit, M.J., 1999. The Karoo Supergroup revisited and Madagascar-Africa fits. Journal of African Emh Sciences. Vol. 29, No. 1, pp. 13% 151, 1999.

Rajaprian, K., Singh, K., Vinoth, M., Kumar, V., Kumar, R. S., 2014. Metamorphism and deformation of mafic and felsic rocks in Bhavani Shear Zone, Tamilnadu, India. International Journal of Advanced Geosciences, 2 (1) 13-19.

Rabinowitz, P.D., Coffin, M.F., Falvey, D., 1983. The separation of Madagascar and Africa. Science 220, 67–69.

Ramana, M. V., V. Subrahmanyam, K. V. L. N. S. Sarma, G. P. S. Murty, G. S. Mittal,and R. K. Drolia, 1994. Magnetic study in the northern Bay of Bengal,Mar. Geophys. Res., 16, 237–242.

Ramana, M. V., Ramprasad, T., and Desa, M., 2001. Seafloor spreading magnetic anomalies in the Enderby Basin, East Antarctica, Earth Planet. Sci. Lett., 191, 241–255.

Ramana, M. V., 1994. Mesozoic anomalies in the Bay of Bengal, Earth Planet. Sci. Lett., 121, 469–475.

Rasoamalala, V., Salvi, S., Béziat D., Ursule, P., Cuney, M., de Parseval Ph., Guillaume, D., Moine, B., Andriamampihantona, J., 2014. Geology of bastnaesite and monazite deposits in the Ambatofinandrahana area, central part of Madagascar: An overview. Journal of African Earth Sciences 94, 128–140.

Raillard, S., 1990. Les marges de l'Afrique de l'Est et les zones de fracture associées; Chaine Davie et Ride du Mozambique, Ph.D. thesis, Laboratoire de Géodynamique sous-marine Villefranche-sur-mer et Département de Géologie Océanique Paris, Université Pierre et Marie Curie.

Rasoamalala, V., Salvi, S., Béziat D., Ursule, P., Cuney, M., de Parseval Ph., Guillaume, D., Moine, B., Andriamampihantona, J., 2014. Geology of bastnaesite and monazite deposits in the Ambatofinandrahana area, central part of Madagascar; An overview. Journal of African Earth Sciences 94, 128–140.

Rea, D.A., and Dixon, M.J., 1983. Late Cretaceous and Paleogene tectonic evolution of the North Pacific Ocean. Earth and Planetary Science Letters, 65, 145-166.

Rekha, S., Bhattacharya, A., Chatterjee N., 2014. Tectonic restoration of the Precambrian crystalline rocks along the west coast of India; Correlation with eastern Madagascar in East Gondwana. Precambrian Research 252, 191–208.

Reeves, C., de Wit, M., 2000. Making ends meet in Gondwana; retracing the transforms of the Indian Ocean and reconnecting continental shear zones. Terra Nova 12, 272–280.

Reeves, C. and Mahanjane, E.S., 2013. Mozambique and its role in the downfall of Gondwana. Geological Society of Houston/Petroleum Exploration Society of Great Britain, 11– 12 September 2013, London.

Reeves, C., 2014. The position of Madagascar within Gondwana and its movements during Gondwana dispersal. Journal of African Earth Science 94, 45-57.

Reeves, C., Teasdale, J.P. and Mahanjane, E.S., 2015. Insight into the Eastern Margin of Africa from a new tectonic model of the Indian Ocean. In Nemcok, M., Rybar, S., Sinha, S.T., Hermeston, S.A. and Ledvényiova , L. (eds), Transform Margins; Development, Controls and Petroleum Systems. Geological 256 Society, London, Special Publications, 431, http;//doi.org/10.1144/SP431.12

Reeves, C.V., Teasdale, J.P., and Mahajane, E.S., 2016: Insight into the Eastern Margin of Africa from a new tectonic model of the Indian Ocean. Geological Society, London, Special Publications, 431, http://doi.org/10.1144/SP431.12.

Ricou, L. E., Besse, J., Marcoux, J. and Patriat, P., 1990. Une reconstruction du Gondwana révisée à partir de données pluridisciplinaires. C. R. Acad. Sci. Park, t. 3ll, Série IL 463469.

Riedel, S. Jacobs, J. Jokat, W., 2013. Interpretation of new regional aeromagnetic data over Dronning Maud Land (East Antarctica). Tectonophysics 585, 161–171.

Riley, T.R., Leat, P.T., Curtis, M.L., Millar, L.L., Fazel, A., 2005.Early-Middle Jurassic dolerite dykes from western Dronning Maud Land (Antarctica): identifying mantle sources in the Karoo large igneous province. Journal of Petrology 46, 1489–1524.

Riley, T.R., Knight, K.B., 2001. Age of pre-break-up Gondwana magmatism; a review. Antarctic Science 13, 99–110.

Riley, T.R. et al., 2004. U-Pb zircon (SHRIMP) ages for the Lebombo rhyolites, South Africa: refining the uration of Karoo volcanism. Journal of the Geological Society London, 161: 547-550.

Riley, T.R. et al., 2006. Overlap of Karoo and Ferrar Magma Types in KwaZulu-Natal, South Africa. Journal of Petrology, 47(3): 541-566.

Rocco, I., Lustrino, M., Zanetti, A., Morra, V., Melluso, L., 2013. Petrology of ultramafic xenoliths in Cenozoic alkaline rocks of northern Madagascar (Nosy Be Archipelago). J. S. Am. Earth Sci. 41, 122–139.

Rogers, R.R., Rogers, K.C., Munyikwa, K., Terry, R.C. and Singer, B.S., 2004. Sedimentology and taphonomy of the upper Karoo-equivalent Mpandi Formation in the Tuli Basin of Zimbabwe, with a new 40Ar/39Ar age for the Tuli basalts. Journal of African Earth Sciences, 40: 147-161.

Sahabi, M., Aslanian, D. andOlivet, J.-L., 2004. Un nouveau point de départ pour l'histoire de l'Atlantique 257 Central. Compte Rendus Geosciences, 33, 1041-1052.

Sahabi M., 1993. Modèle général de l'évolution de l'océan Indien. Thèse de Doctorat. Univ. Bretagne Occ., Brest, (vol. 1) et (vol. 2).

Salman, G., Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sediment. Geol. 96, 7–41.http;//dx.doi.org/10.1016/0037-0738 (95)00125-R.

Sandwell, D. T. and Smith,'Iry'. H. F., 1992. Global marine gravity from ERS-I, Geosat and Seasat Reveals New Tectonic Fabric. EOS, A. G. U.73, no43

Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E., Francis, R., 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. Science 346, 65–67.

Sanders, L.D., 1957. The tectonic framework of Upper Paleozoic sedimentation in Kenya, Seccion V: Relaciones entre la tectonica y la sedimentacion. Congreso Geologico Internacional, XX Sesion, Mexico 1956, Mexico, pp. 363-371.

Schlich, R., Simpson, E.S.W., Gieskes, J., Girdley, W.A., Leclaire, L., Marshall, B.V., Moore, C., Muller, C., Sigal, J., Valuer, T.L., White, S.M. and Zobel, B., 1974. DSDP Site 241, Initial report of the Deep Sea Drilling Project. Washington DC, 87-138.

Schlich' R. and Fondeur, C., 1974. Anomalies magnétiques crétacées dans le bassin des Mascareignes (Ocfun Indien). C. R. Acad. Sci. Paris, 278, 541-544

Sclater, J.G., and Fisher, R.L., 1974, The evolution of the east central Indian Ocean with emphasis on the tectonic setting of the Ninetyeast Ridge; Geol. Soc. America Bull., 85, 683-702.

Scheffler, K., Hoernes, S. and Schwark, L., 2003. Global changes during Carboniferous-Permian glaciation of Gondwana: linking polar and equatorial climate evolution by geochemical proxies. Geology, 31(7): 605-608.

Schlueter, T., Picho-Olarker, G. and Kreuser, T., 1993. A review of some neglected Karoo grabens of Uganda. Journal of African Earth Sciences, 17, 415-428.

Scotese, C. R., Gahagan, L. M. and Larson, R. L., 1988. Plate tectonic reconstructions of the Cretaceous and Cenozoic ocean basins. Tectonophysics, 155, 27-48.

Searle, R. C., R. T. Bird, R. I. Busby, D. F., 1993. Naar, The development of two oceanic microplates: Easter and Juan Fernandez microplates, East Pacific Rise, J. Geol. Soc., London, 150, 965–976.

Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shepard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S. and Chandler, M., 2012. Global continental and ocean basin reconstructions since 200 Ma. EarthScience Reviews, 113, 212-270.

Segoufin, J., 1978. Anomalies magnétiques mésozoïque dans le bassin de Mozambique. Comptes Rendus de l'Académie des Sciences Paris, Série D t. 287, 109–112.

Segoufin, J., Patriat, P., 1981. Reconstruction de l'Océan Indien occidental pour les époques des anomalies M21, M2 et 34. Paléoposition de Madagascar. Bulletin de la Société Géologique de France 23, 603–607.

Simpson, E.S.W., Sclater, J.G., Parsons, B., Nortion, I.O., Meinke, L., 1979. Mesozoic mag-netic lineations in the Mozambique basin. Earth and Planetary Science Letters 43, 260–264.

Sioni S. 1996. Mer Ionienne et Apulie depuis l'ouverture de l'Océan Alpin. Thèse de Doctorat.Univ. Bretagne Occidentale

Smith, A.G. and Hallam, A., 1970. The fit of the southern continents. Nature, 225; 13Q- 144.

Smith, R.M.H., 2000. Sedimentology and Taphonomy of Late Permian vertebrate fossil localities in Southwestern Madagascar. Palaeontologica africana, 36: 25-41.

Smith, R.M.H., 1995. Changing fluvial environments acrossthe Permian-Triassic boundary in the Karoo Basin, South Africa and possible causes of tetrapod extinctions. Palaeogeography, Palaeoclimatology, Palaeoecology, 117: 81-104.

Smith, R.A., 1984. The lithostratigraphy of the Karoo Supergroup in Botswana. Bulletin of the Geological Survey Department of Botswana, 26: 239p.

Snider-Pellegrini, A. La Création et ses mystères dévoilés (Creation and its mysteries revealed) (Paris, France; Frank et Dentu, 1858), plates 8 and 9 (pages 314 and 315).

Storey, B. C., The role of mantle plumes in continental breakup: case histories from Gondwanaland, Nature, 377, 301–308, 1995.

Storey, M., Mahoney, J.J. and Saunders, A.D., 1997. Cretaceous basalts in Madagascar and the transition between plume and continental lithosphere mantle sources. In: J.J. Mahoney and M.F. Coffin (Editors), Large igneous provinces: continental, oceanic and planetary flood volcanism. American Geophysical Union, Geophysical Monograph, Washington D.C., pp. 95-122.

Stollhofen, H., 1999. Karoo Synrift-Sedimentation und ihre tektonische Kontrolle am entstehen Kontinentalrand Namibias. Zeitschrift der deutschen geologischen Gesellschaft, 149: 519632.

Suisse, E., 1924. La tectonique de lAsie. Conference faite a Bruxelles le 10 aout 1922. Congres geol. int. (13me session). C.R. de la 13me session, fasc. 1,171-372. Liege: Vaillant-Carmanne, 1924.

Svensen, H., Corfu, F., Polteau, S., Hammer, Ø., Planke, S. 2012. Rapid magma emplacement in the Karoo Large Igneous Province. Earth and Planetary Science Letters 325–326 (2012) 1–9.

Tankard, A., Welsink, H., Aukes, P., Newton, R., Stettler, E., 2009. Tectonic evolution of the Cape and Karoo basins of South Africa. Marine and Petroleum Geology 26 (2009) 1379–1412.

Tarling, D.H., 1972. Another Gondwanaland. Nature, 238; 92-93. Veevers, J. J., Jones, J. G. and Talent, J.A., 1971. Indo-Australian stratigraphy and the configuration and dispersal of Gondwanaland. Nature, 229; 383-388.

Thomas, R.J., Agenbacht, A.L.D., Cornell, D.H., Moore, J.M., 1994. The Kibaran of southern Africa; tectonic evolution and metallogeny. Ore Geol. Rev. 9, 131–160.

Thomas, R.J., Jacobs, J., Weber, K., 1997. Geology of the Mesoproterozoic Cape Meredith Complex, West Falkland. In; Ricci, C.A.(Ed.), The Antarctic Region; Geological Evolution and Processes. Terra Antartica Publication, Siena, pp. 21–30

Thomas, R.J. et al., 1992. Geological studies in southern Natal and Transkei: Implications for the Cape Orogen. In: M.J. de Wit and I.G.D. Ransome (Editors), Inversion tectonics of the Cape Fold Belt, Karoo and Cretaceous basins of Southern Africa. A.A. Balkema, Rotterdam, pp. 229-236.

Thompson, A.O., 1956. Geology of the Malindi Area, 36. Geological Survey of Kenya, Nairobi, Kenya, 63 pp.

Thompson, G., Bryan, W.B., Frey, F.A., Dickey, J.S. & Davies, H., 1982. Petrology, geochemistry and original tectonic setting of basalts from the Mozambique Basin and Ridge (DSDP Sites 248, 249 and 250), and from the Southwest Indian Ridge (DSDP Site 251), Mar. Geol., 48, 175–195.µ

Tikku, A.A., Karen M. Marks, K.M., Kovacs, L.C., 2002. An Early Cretaceous extinct spreading center in the northern Natal valley. Tectonophysics 347, 87–108.

Torsvik, T., Müller, R.D., Van der Voo , R., Steinberger, B. and Gaina, C., 2008. Global plate motion frames; toward a unified model, Reviews of Geophysics, 46, RG3004, 1-44

Torsvik, T., Van der Voo , R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P. V., van Hinsbergen, D.J.J., Domeier, M., Gaina, C., Tohver, E., Meert, J.G., McCausland, P.J.A. and Cocks, L.R.M., 2012. Phanerozoic polar wander, palaeogeography and dynamics. Earth-Science Reviews, 114, 328-365.

Torsvik, H., Cocks, L.R.M., 2013. Gondwana from top to base in space and time. Gondwana Research 24, 999–1030.

TuchoIke, B.E., Houtz, R.E. and Barrett, D.M., 1981. Continental crust beneath the Agulhas Plateau. Southwest Indian Ocean. J. Geophys. Res., 86; 3791-3806.

Tucker, R.D., Roig, J.Y., Delor, C., Amelin, Y., Goncalves, P., Rabarimanana, M.H., Ralison, A.V., Belcher, R.W., 2011a. Neoproterozoic extension in the greater Dharwar craton; a re-evaluation of the Betsimisaraka suture in Madagascar. Canadian Journal of Earth Science 48, 389–417.

Tucker R.D., Roig, J.Y., Moine B., Delor C., Peters S.G., 2014. A geological synthesis of the Precambrian shield in Madagascar. Journal of African Earth Science 94, 9-30.

Uenzelmann-Neben, G., Gohl, K., Ehrhardt, A., 1999. Agulhas Plateau, SW Indian Ocean; new evidence for excessive volcanism. Geophysical Research Letters 26 (13), 1941–1944.

Uenzelmann-Neben, G., Schlüter, P. and Weigelt, E., 2007. Cenozoic oceanic circulation within the South African gateway: indications from seismic stratigraphy. South African Journal of Geology, 110: 275294

Veevers, J.J., 2009. Palinspastic (pre-rift and -drift) fit of India and conjugate Antarctica and geological connections across the suture. Gondwana Research 16 (2009), 90–108.

Veevers, J.J., Cole, D.I. and Cowan, E.J., 1994. Southern Africa: Karoo Basin and Cape Fold Belt. In: J.J. Veevers and C.M. Powell (Editors), Permian-Triassic Pangean Basins and Foldbelts along the Panthalassa Margin of Gondwanaland: Boulder. Geological Society of America, Colorado, pp. 223279.

Verniers, J., Jourdan, P.P., Paulis, R.V., Frasca-Spada, L. and De Bock, F.R., 1989. The Karoo Graben of Metagula, Northern Mozambique. Journal of African Earth Sciences, 9(1): 137158

Verrier, F. Leprêtre, A.., Evain, M., Schnurle, P., Watremez, L,Aslanian, D., De Clarens, P., Afonso, N., Afilhado, A. Leroy, d'Acremont, E,, Castilla, R., Moulin, M., 2017. Preliminary results from combined wide-angle and reflection seismic data in the Natal Valley, South Mozambique margin across the Almirante Leite volcanic ridge: MZ2 profile (MOZ3/5 cruise).EGU Poster.

Viola, G., Henderson, I.H.C., Bingen, B., Thomas, R.J., Smethurst, M.A., de Azavedo, S., 2008. Growth and collapse of a deeply eroded orogen: insights from structural and geochronological constraints on the Pan-African evolution of NE Mozambique. Tectonics 27, TC5009, doi:10.1029/2008TC002284.

Virlogeux, P., 1987. Géologie de la marge nord-mozambique et de la chaîne Davie (9°S à 21°S). (Campagne MD40-MACAMO, Thèse d'Université, dactyl) Univ. P. et M. Curie, Paris.

Visser, J.N.J., 1995. Post-glacial Permian stratigraphy and geography of southern and central Africa: boundary conditions for climatic modelling. Palaeogeography, Palaeoclimatology, Palaeoecology, 118(3-4): 213-243.

Visser, J.N.J., 1996. Controls on Early Permian shelf deglaciation in the Karoo Basin of South Africa. Palaeogeography, Palaeoclimatology, Palaeoecology, 125(1-4): 129-139.

Visser, J.N.J. and Loock, J.C., 1982. An investigation of the Basal Dwyka Tillite in the Southern Part of the Karoo Basin, South Africa. Transactions of the Geological Society of South Africa, 85: 179-187.

Visser, J.N.J. and Loock, J.C., 1987. Ice margin influence on glaciomarine sedimentation in the PermoCarboniferous Dwyka Formation from the southwestern Karoo, South Africa. Sedimentology, 34: 929-941.

Walford, H.L. and White, N.J., 2005. Constraining uplift and denudation of West African continental margin by inversion of stacking velocity data. Journal of Geophysical Research, 110: BO4403.

Wanke, A., 2000. Karoo-Etendeka Unconformities in NW Namibia and their Tectonic Implications, Bayerischen JuliusMaximilians-Universität Würzburg, Würzburg, 113 p. pp.

Wanke, A., Stollhofen, H., Stanistreet, I.G. and Lorenz, V., 2000. Karoo unconformities in NW-Namibia and their tectonic implications. Communications of the geological Survey of Namibia, 12: 259-268.

Ward, P.D., Montgomery, D.R. and Smith, R., 2000. Altered river morpholoy in South Africa related to the Permian-Triassic extinction. Science, 289: 1740-1743.

Watkeys, M.K., 2002. Development of the Lebombo rifted volcanic margin of southeast Africa. In: M.A. Menzies, S.L. Klemperer, C.J. Ebinger and J. Baker (Editors), volcanic rifted margins. Geological Society of America, Special Paper, Boulder, Colorado, pp. 27-46.

Watkeys, M.K. and Sokoutis, D., 1998. Transtension in southeastern Africa associated with Gondwana break-up. In: R.E. Holdsworth, R.A. Strachan and J.F. Dewey (Editors), Continental transpressional and transtensional tectonics. Geological Society, London, Special Publications, pp. 203-214.

Watson, S.J., Whittaker, J.M., .Halpin, J.A., Williams, S.E., Milan, L.A., Daczko, N.R., Wyman, D.A., 2016. Tectonic drivers and the influence of the Kerguelen plume on seafloor spreading during formation of the early Indian Ocean. Gondwana Research 35, 97–114.

Weiss, R.H., 2001. Middle to Late Permian microfloral assemblages from the Ruhuhu and Selous basins, Tanzania. In: R.H. Weiss (Editor), Contributions to geology and palaeontology of Gondwana in honour of Helmut Wopfner. Geological Institute, University of Cologne, Cologne, pp. 497529.

White, R., McKenzie, D., 1989. Magmatism at rift zones; the generation of volcanic conti-nental margins andflood basalts. Journal of Geophysical Research 94 (B6), 7685–7729.

White, R.S., Spence, G.D., Fowler, S.R., McKenzie, D.P., Westbrook, G.H., Bowen, A.N., 1987. Magmatism at rifted continental margins. Nature 330, 439–444.

White, R.S., 1997. Mantle plume origin for the Karoo and Ventersdorp flood basalts, South Africa. South African Journal of Geology, 100(4): 271-282.

Williams, S.E., Whittaker, J. D. and Muller, R. D., 2013. Newly recognised continental fragments rifted from the West Australian margin. In; West Australian Basins Symposium, Perth, 18–21 August, 2013, 1–10.

Windley, B.F., Razafiniparany, A., Razakamanana, T., Ackermand, D., 1994. Tectonic framework of the Precambrian of Madagascar and its Gondwana connections; a review and reappraisal. Geol. Runds. 83, 642–659.

Windley, B.F., Razafiniparany, A., Razakamanana, T., Ackermand, D., 1994. Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: a review and reappraisal. Geol. Runds. 83, 642–659

Wopfner, H., 1993. Pangean depositional sequences between Karoo and Lut. In: U. Thorweihe and H. Schandelmeier (Editors), Geoscientific research in Northeast Africa.

Wopfner, H. and Kaaya, C.R., 1991. Stratigraphy and morphotectonics of Karoo deposits of the northern Selous Basin, Tanzania. Geological Magazine, 128: 319-334.

Wopfner, H., 2002. Tectonic and climatic events controlling deposition in Tanzanian Karoo basins. Journal of African Earth Sciences, 34(3-4): 167-177.

Wopfner, H. and Diekmann, B., 1996. The Late Palaeozoic Idusi Formation of southwest Tanzania: a record of change from glacial to postglacial conditions. Journal of African Earth Sciences, 22(4): 575-595.

Wright, R.P. and Askin, R.A., 1987. The Permian-Triassic boundary in the Southern Morondava Basin of

Madagascar as defined by plant microfossils. In: G.D. McKenzie (Editor), Gondwana six: Stratigraphy, Sedimentology, and Paleontology. American Geophysical Union, Geophysical Monograph, Washington D.C., pp. 157-166.

Zaffarana, C.B., López de luchi, M.G., Somoza, R., Mercader, R., Giacosa, R., Martino, R.D., 2010. Anisotropy of magnetic susceptibility study in two classical localities of the Gastre Fault System, central Patagonia. Journal of South American Earth Sciences 30, 151-166.

www.portal.gsi.gov.in/portal 11/07/2016

Article submitted.

ARTICLE TO EARTH SCIENCE REVIEWS SUBMITTED

Article submitted.

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

J. O. Thompson[a)] M. Moulin[a)] D. Aslanian [a)] P. de Clarens[b], F. Guillocheau[c]

[a)] Institut Français de Research pour l'Exploration de la Mer (IFREMER), Laborataire de Geodynamique et d'enregistrements Sédimentaires (LGS), Plouzané, France.

[b)] Total, Exploration Production/Géosciences/Projets Nouveaux/Expertise Géodynamique, 2, place de la Coupole - La Défense 6, 92078 Paris la Défense Cedex, France.

[c)] Department of Geoscience, Université de Rennes 1/CNRS (UMR 6118), Rennes, France.

Keywords

Plate tectonics, Gondwana, PanAfrican structures, Amalgamation, Indian Ocean

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 lack of consensus on the nature of major structures and basins in the ocean. Past attempts to reconstruct the initial fit of 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 they pose, 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 of Gondwana's initial geometry 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 Pamela MOZ3-5 expedition in the Northern Mozambique Ridge and Northern Natal Valley that discovered the two basins to be underlained by about 35km of continental crust. 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 can be extended.

1.1 Introduction

The formation of Gondwana during the PanAfrican Orogeny and its subsequent fragmentation in the Mesozoic saw the largest unit of continental crust on earth live for more than 200Ma, but the question of the initial geometry of this superlandmass remains unanswered and a challenge to geologist. Any attempt to describe the plate tectonic history of Gondwana must first start with a discussion of the initial fit of the tectonic plates. However, reconstruction models of the Indian Ocean are characterized by gaps, 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 (McKenzie & Sclater, 1971; Smith & Hallem, 1970; Tarling *et al.* 1972; 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.*, 2015; Davis *et al.*, 2016) (Figure 1). These margins recorded the oldest sediments and magnetic anomalies of the Indian Ocean, and therefore crucial to our understanding of the initial configuration of Gondwana and its early breakup history at Jurassic time. Although the Cenozoic kinematic of the ocean is well constrained between the plates (Bernard *et al.*, 2005), little is known about the initial geometry of Gondwana and its immediate pre-breakup history, due to 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 set, leading to diverse initial fit positions (Figure 2 and supplementary material). Researchers adopt different approaches to the reconstruction modeling (for eg; Konig & Jokat, 2006, Eagles and Konig, 2008; Torsvik *et al.*, 2012; Gaina *et al.*, 2013, Nguyen *et al.*, 2016, Davis *et al.*, 2016) adopt a model based on geophysical data (Gravity and magnetic data). Tarling *et al.*, 1972 and Powells *et al.*, 1980 are based on onshore geological data, with less consideration of geophysical data. Torsvik *et al.*, 2008, 2012; Muller *et al.*, 1997 are based on hotspot tracks. Last some others consider only a part of the problem by focusing in a specific area without regard to the far consequences (eg Klimke & Franke, 2016). However, the ever increasing sets of constraints from new geological and geophysical discoveries, imposes that the tectonic plates cannot be moved about without adequate geological and geophysical basis (Dingle and Scrutton, 1974; Tarling *et al.*, 1972), and therefore all efforts to reconstruct the plates must embrace a more broader approach, in a true global view (Sahabi *et al.*, 2004; Labails *et al.*, 2010; Aslanian & Moulin, 2012).

Here we attempt within the framework of the PAMELA (Passive Margin Exploration Laboratories) project, which is an integrated research co-funded by TOTAL, IFREMER, in collaboration with Université de Bretagne Occidentale, Université Rennes 1, Université Pierre and Marie Curie, CNRS et IFPEN, on passive margins across the globe, to highlight these varied differences and incoherencies in current published models (McKenzie & Sclater, 1971; Smith & Hallem, 1970; Tarling *et al.*, 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.*, 2015; Davis *et al.*, 2016) (Figure 2 and supplementary material) by plotting 10 of such models on the same scale to compare them. These 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) overlap across the African continent and the Mozambique ridge some hundreds of kilometers raising questions as to the nature of crust underlying these areas and the implication on the N-S Limpopo Margin and the connected Fracture zone. In addition, they pose questions as to the true latitudinal and angular position of Madagascar and India relative to Africa as their positions vary widely in these models, which in turn imply different pair of conjugate passive margins; posing difficulty in deciphering which model to adopt as base for further work. We present a new model of East-West Gondwana's initial fit base on analysis and combination of onshore and offshore geological and geophysical data. Mahanjane (2012) presented seismic reflection result in support of continental origin for the High. Mueller et al. (2016) analyzing seismic refraction and gravity supported same. Recent seismic refraction acquisition in the Limpopo and Natal Basins during the PAMELA-MOZ3-5 expedition discovered evidence in favor of 30-35 km thick continental crust underlying the two basins (Lepretre *et al.*, 2017; Verrier *et al.*, 2017). The new data imply these structures existed in Gondwana and therefore adequate space must be created for their accommodation.

1.2 Previous reconstruction models

Notwithstanding the several dedicated effort and scientific knowledge that confirms the continental drift processes and the Wilson cycle (eg Rodinia, Gondwana, Pangea, etc…), a crucial scientific question which still remain unanswered is: what was the true geometry of Gondwana and how did its disintegration occurred? 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 provided 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.*, 2015; Davis et al., 2016; Klimke and Franke, 2016) of Figure 2.

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

In the models of (Sahabi, 1993; Leinweber & Jokat, 2012; Reeves *et al.*, 2015; Davis *et al.*, 2016), Madagascar is fitted more angular to Africa, as opposed to that of Gaina *et al.* (2013) and Klimke and Franke (2016), that the position is relatively north-south. Beside the fact that this divergence implies different conjugate passive margin for the Majunga Basin and therefore has strong consequences on the understanding 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 (eg Mad/India/Ant). Reeves et al. (2015) imply overlap between the Africa plate and a part of Madagascar which if is true must answer the nature of crust underlying the overlapping areas and the conjugate basins of Morondava and Majunga or the existence of an important intraplate deformation in the Tanzania area.

Southwards with a focus on the Antarctica Plate (Figure 3b), Leinweber and Jokat (2012), Gaina *et al.* (2013) and Reeves *et al.* (2015) all overlap the Antarctic plate across the Limpopo basin, 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 overlap, considering continental origin for same. 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 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 Mozambique basin; the oldest oceanic crust in Mozambique basin (Whether magnetic anomaly M41 (166Ma, Leinweber et al., 2012) represent the first ocean in the basin or may correspond to magmatic underplating (see also Mueller and Jokat, 2017)), and the crustal nature of the Mozambique and Madagascar aseismic ridges.

2. Methology

Producing as much as possible holistic and coherent reconstruction of the India Ocean demands a multifaceted approach (Aslanian *et al.*, 2009; Moulin *et al.*, 2010; Aslanian & Moulin, 2012) by 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 the adjoining plates, in a global view, and to produce a model that is consistent and respect current data interpretations and field observations.

We first carried out a comprehensive examination of a number of large, but not complete published kinematic reconstruction models of the Indian Ocean, (more than 30 since 1977) to compare them on the same scale using PLACA and PLACA4D software (Matias *et al.*, 2005), looking at their consequences on the continental passive margins and predictions on the nature and origin of the Mozambique and Madagascar aseismic ridges. These models were subsequently grouped into broad families.

We then undertook a compressive study of the basement of the plates: locking at the architecture and geochronological composition of their constituent Cratons and crustal blocks and delineating important structural markers in order to accurately juxtapose them to each other to obtain a more coherent initial fit. Indeed, Gondwana formed during the PanAfrican Orogeny from 720 to 550Ma (Jacobs *et al.*, 2003; Guiraud *et al.*, 2005), consisting of Archean and Paleoproterozoic Cratonic cores, surrounding accreted progressively younger terrains of Mesoproterozoic and Neoproterozoic age (Jacobs *et al.*, 2003; Dewaele, 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 marginal and rifts basins is very critical to unraveling the initial geometry of Gondwana and its disintegration.

A compilation of onshore and offshore geological and geophysical data in the Indian Ocean that could be accessed was therefore carried out, to understand the work that has already been done, 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 the Karoo event along the east African margin, and within the African plate were examined, and compared to Karoo events in Madagascar, Antarctica, and Australia to examine the different lithologic sequences that were deposited from the Late Carboniferous to Recent, and to also understand the evolution history of these basins.

A full-fit reconstruction needs to take into account the morphology and the nature of the passive margins as well as the main structural oceanic features produced by the break-up and the 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 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 better help constrain the initial fit. The plotting of the maps presented here was achieved with the help of Arcgis 10.2, PLACA (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 that has deformed the shape of the coastlines since the break-up, and/or the presence of continental material offshore the coasts. If no evidences of such material or deformation are observed, the reconstruction must be modified (Moulin *et al.*, 2010; Aslanian & Moulin, 2012). Therefore, in a given reconstruction, an overlap must be 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 a same way, a gap must be either explained by the existence of continental block off shore and/or by the existence of a range on the back 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).

It is important to note that this fit represents only the shape of Gondwana at the time of the fit and does not take into account the deformations that occurred before that time as the model of Reeves *et al.*, (2016) try to do.

Reeves *et al.*, (2016) assume, by analogy with actual 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 block at 182.7 Ma with a separation of about twice the typical crustal thickness (i.e. about 80 km, but +/- 20 km). The model of Reeves *et al.*, (2016) presents therefore a tentative of reconstruction of the Gondwana, 20Ma before the break-up (and our reconstruction).

Whilst this attempt is a good first approximation which needs as these authors wrote: « More works need to be done to quantify [their] assumption » (the actual knowledge on the morphology of actual margins all over the world presents a very different view of Passive margin, with very different morphologies), it seems to us more sensitive to separate the pre-beak-up evolution in two steps, as we get more and more geophysical data and evidences on the margins and offshore. Having a good reconstruction at the break-up time will give us a good base to go back and test Reeves *et al.* hypothesis.

Finally, all our findings and interpretations from the different data sources were combined to propose a new pre-break-up fit of Gondwana. In May 2016, new wide-angle data were acquired in the Limpopo Basin and the Natal valley (Moulin & Aslanian, 2016; Moulin & Evain, 2016; Lepretre et al., 2017) to determine the nature of the crust in these two basins. They discovered continental crust, about 35km underlying the two basins. Their findings is 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 plate share similar age and orogenic history with three neighboring plates (Africa, India and Australia) (Boger, 2011). We have compiled from (Kelly *et al.*, 2002; Ghosh *et al.*, 2004; Boger, 2011; Rediel *et al.*, 2013) the geology of Antarctica (Figure 4) and from (Daly et al., 1989: Dewaele, 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 trends between the two plates.

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 eg 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)

The Kaapvaal Craton 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; Dewaele, 2003; Guiraud *et al.*, 2005; Jacobs *et al.*, 2008; Rekha *et al.*, 2014; Rediel *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 was placed south of the Mozambique belt in Gondwana (Thomas *et al.*, 1994; Jacobs *et al.*, 2008; Rediel *et al.*, 2013) (Figure 5).

The Namaqua-Natal belt 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; Reidel *et al.*, 2013), with the main collisional event taking place at 1135Ma (Rekha *et al.*, 2014; Rediel *et al.*, 2013). It represents one of the very few areas of Mesoproterozoic crust in Gondwana that lacks significant overprint of PanAfrican orogenic event (Jacobs *et al.*, 2003, 2008; Rediel *et al.*, 2013). In Antarctica, the Mesoproterozoic orogenic and magmatic activity that formed the Maud Belt has been dated between 1171±25 to 1045±9Ma (Jacobs *et al.*, 1998, 2003), near contemporaneous with the Namaqua-Natal event. Meaning these two events may be linked into one single Namaquan-Natal-Maud orogenic belt (Jacobs *et al.*, 2008). This provides some important evidence in support of the Antarctic plate situating south of Mozambique at least during the Mesoproterozoic times (Jacobs *et al.*, 2008; Rediel *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 (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; Rediel *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 the many reconstructions of (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.*, 2015; Nguyen *et al.*, 2016), Antarctica (Grunneghona) overlap directly the Limpopo basin some 300 km from the Mozambique shoreline. This assumption, imply oceanic crust in the Limpopo basin, and has serious implications on the temporal and spatial evolution of the Mozambique margin.

Aeromagnetic studies of dyke swarms of the Lebombo Mountains have been associated with rifting of Gondwana (Watkeys, 2002; Reeves 2000; Reeves & Mahanjane, 2012; 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, to be related to the initial east-west separation of Africa and Antarctica.

Duncan *et al.* (1997), Klausen (2009), Hastie *et al.* (2014) postulate the basin to be floored by Karoo volcanics younging seaward from the Lembobo range (Watskey, 2002; Klausen, 2009), and the Karoo volcanic event having resulted in the breakup of Gondwana. However, the evolution proposed by Klausen (2009) implies a main NW-SE movement of the Antarctica plate with respect to Africa, which is not coherent with the N-S Limpopo margin orientation. Moreover, the geological analysis of the Karoo rocks (Melluso *et al.*, 2008) onshore in the Limpopo Basin shows a composition, that is not of MORB composition, nor SDRs, as is inferred by all models, that overlap Africa and Antarctica.

Bristow (1980) observed that the Karoo basalts show both enriched and depleted mantle sources, and therefore predicted that these basalts have been sourced differently. He also observed that the rhyolites have high Sr and Ba components, with enrichment in K and Na compositions. He therefore predicted that these rhyolites may have been sourced from the partial melting of previously underplated basaltic magma which may have contaminated the magma leading to the high Sr, K and Na contents. His work reinforces the different source origins of the Karoo magma.

Flores (1964), on the hand observed that, instead of a continuous sheet of Karoo effusive underlying the basin, the basin maybe characterized by series of parallel trending fractures issuing ever younger magma. Domingues *et al.* (2016) applied seismic ambient noise tomography in the basin, and observed low crustal velocities along with a thinning of the crust. They interpreted a possible transitional crust, with crustal thickness between 20 and 30 km. They agreed with Flores, noting that the emplacement mechanism suggested by him may have led to some magnetic signatures.

Lastly, preliminary results from recent seismic refraction and reflection data acquisition in the basin (Lepretre *et al.*, 2017; Verrier *et al.*, 2017) suggest that the Natal Basin may not be underlain by oceanic crust, but 35km thick crust probably of continental nature. This will be in contrast to models that require overlap of Antarctica across the basin.

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

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 and www.portal.gsi.gov.in/portal 11/07/2016) (Figure 6).

Rocks of the Archean Napier complex of East Antarctica links well into the Eastern Ghats shield during the Mesoproterozoic times (Kelly *et al.*, 2002: Ghosh *et al.*, 2004) together forming the “Indo-Napier segment’’ described by (Kelly *et al.*, 2002). The segment collided with East Antarctic basement in Mesoproterozoic during the amalgamation of Rodinia Supercontinent (Fitzsimons, 2000) producing the crustal fragments constituting the Rayner Complex. The Rayner Complex extends from Enderby Land into the Eastern Ghats Granulite Belt in India (See our model Figure 18).

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 permits a good juxtaposition of India to Antarctica in Gondwana. The data is further strengthen by the conjugate Gondwanan sequence of Godavari and Mahanadi in Eastern India, and the Lambert and Robert rift valleys of Eastern Antarctica which trends between 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 & DePaolo (1991) and Boger (2011) (Figure 7).

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

The Beardmore Craton of Antarctica also bears similar geochronogical properties with the Curnamona Craton in Australia. According to Boger (2011), the Curnamona-Beadmore blocks collided with the Mawson Craton during the Paleoproterozoic Nimrod–Kimban orogenesis (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 conjugate in Antarctica bearing similar geochemical and age characteristics.

The above geological data combine with the recorded geophysical data (Magnetic anomaly from anomaly C34 to C0 (Cande and Mutter, 1982)), gravity and bathymetry data between the plates makes 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; Nesen *et al.*, 1988: de Wit al., 2001; Rasoamalala *et al.*, 2014; Tucker *et al.*, 2014: Rekha *et al.*, 2014) (Figure 8).

The Archean rocks in Madagascar is represented by Archean rocks outcropping in Antongil and Fenoarivo, 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 trace of important geological structures into the two plates and their juxtaposition to each other.

In addition, the Moyar, Karrur Kambam, and Palghat 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 (Angavo-Ifanadiana, Ranostara and Batsimisaraka 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 collided with the Tanzania Craton 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) around Madagascar. The protolith of the Bur Acaba 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 may suggest that the Craton may have extended into Bur Acaba and beyond. According to de Wit (2003), Madagascar's east coast originated together with rocks of the Indian Dharwar Craton and were united for more than 3000 Ma.

Other parts of Madagascar have African roots that go back 2500 Ma (de Wit, 2003). The Neoproterozoic granulites, of Madagascar (Vohibory domain) and Africa (The Cabo DelGado nappes of the Mozambique belt) (Bingen *et al.*, 2009 and Tucker *et al.*, 2014) share similar geochemical properties. 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 early Ediacaran time (0.65– 0.63 Ga Tucker *et al.*, 2014).

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

The Falkland Islands is currently agreed by a number of workers (Martin *et al.*, 1982: Martin & Hartnady, 1986; Curtis & Hyam, 1998) to form the 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 in its fit to the 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; 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; Curtis & Hyam, 1998; Jacobs *et al.*, 1998) in favor of the three areas forming continues 1.1Ga Mesoprotorozoic terrain which was accreted to the Kaapval-Grunehogna Craton during the Mesoprotorozoic 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 after Kelley *et al.* (2002), and Tucker *et al.* (2014) (Figure 10). The basement consists of the Paleoproterozoic Highland, Wanni and Vijayan complexes, which were overprinted by the Pan-Africa orogenic event. The Vijayan complex share similar geochronological properties with Lutzow Hölm Complex of Antarctica (Kelley *et al.*, 2002; Bigen *et al.*, 2009; Tucker *et al.*, 2014; Rekha *et al.*, 2014), and therefore allows for reconstruction of Sri Lanka to the Lutzow Hölm area (See our new model Figure 22). In the new model, the prominent 600km 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 (Bingen *et al.*, 2009).

3.2 Paleozoic-margin and basin, and Mountain belts and rifts

The Paleozoic marginal and rift basins of Gondwana preserve the litho-stratigraphy history of the super-continent from the Late Carboniferous to the Middle Jurassic. Gondwana since the Late Carboniferous has experienced varying magnitude of intraplate deformation and volcanism most often centered along pre-existing fractures and faults zones within orogenic mobile belts and Cratonic boundaries (Watkeys & Sokoutis, 1998).

The formation of these basins and their sediment deposition was mainly controlled by 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), to extensional deformation along Eastern Africa and Madagascar margins linking the Tethyan rifts (Kazmin, 1991 and Gnos *et al.*, 1997) to establish the Karoo rift basins along these margins. The rifting was followed by vast intrusion of volcanism in Southern Africa (Lembobo Monocline and Karoo volcanics) and Antarctica (Volcanics of the Dronning Maud Land and the Ferrar Province) characterized by 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 intrusives have shown them to have compositional and age overlaps (Wellman, 1983; Duncan *et al.*, 1997; Elliot & Fleming, 2000; Klausen, 2009; Hastie *et al.*, 2014).

Workers are currently divided on the interpretations and the 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. The Mbuluzi rhyolites and Rooi Rand Dykes (174Ma Ar/Ar; Klausen, 2009) of the Lebombo monocline is 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). However, the analysis of the rocks (Melluso et al., 2008) onshore in the Limpopo Basin shows a composition, which does neither fit a MORB composition nor SDR's.

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 Limpopo Basin; a basin whose crustal nature is still debated. This assumption coupled with the undetermined nature of the Limpopo Basin could potentially result in ~300km overlap or gap between Africa and Antarctica, depending on the interpretation adopted in the reconstruction modeling. It also implies a short period for the rifting event, ending in the Lower Jurassic (Geiger *et al.*, 2004; Hastie *et al.*, 2014).

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 the volcanics with 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. Furthermore, analysis of the rocks onshore in the Limpopo Basin shows a composition, which does neither fit a MORB composition nor SDRs (Revillon, pers. Comm. 2017).

The beginning of fragmentation of Gondwana was accompanied by the formation of a series of Interior Fracture basins (Salman & Abdullah, 1995), which were filled by sediments represented by the Karoo sequence in Africa, Madagascar, Antarctica, Australia and India.

In Madagascar, the Karoo 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 the crustal stretching and thinning.

In Africa, the Karroo 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 basement in southernmost Mozambique (Salman & Abdula, 1995, Mahanjane, 2012). In Southern Africa, it is represented 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 capped by the Lower-Middle Jurassic Karoo Stromberg 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).

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.*, 2013) have shown them to have compositional and age overlaps, granting some common history of their emplacement.

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).

3. 3 Offshore geological constraints

The determination of the true nature and origin of oceanic geological structures is not a straightforward task. Although there has been several attempt to describe the nature of offshore aseismic structures and basins in the Indian Ocean (eg Beira High, Natal Valley, Maurice Ewing Bank, Mozambique and Madagascar ridges and the Limpopo Basin), debates exist on their crustal origins: 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 strong implications on the reconstruction of the Gondwana's initial geometry.

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 true origin of the Beira High was lingering over a long time. Mahanjane (2012), presented seismic reflection data showing extensional deformation, and breakup unconformity reflectors downlapping against the acoustic basement along the eastern flack of the Beira High. His interpretation supports continental origin for the Beira High, in disagreement recent kinematic models (eg Leinweber & Jokat, 2012; Gaina *et al.*, 2013, 2015) that presupposes oceanic origin. Leinweber *et al.*, 2012 interpreted older magnetic series M28-M41 on the crust, and proposed oceanic origin. However, recently Mueller *et al*, (2016) presented seismic refraction and gravity results on the High in support of 20km-thick continental crust, and the Zambezi depression underlained by possible thinned intruded continental crust (Figure 11a). Following the new data from Mueller *et al.*, (2016), models overlapping the Antarctic plate on the continental High may have to be adjusted to create space for its accommodantion, except implying a NW-SE intraplate continental deformation of more than 100km which in not observed onland.

Leinweber *et al.* (2012) suggested the presence of magnetic anomalies M41- M28 in the Zambeze Basin. Some of these magnetic anomalies were identified across the Beira High. Their data was reinterpreted by Mueller and Jokat (2017), who suggested the oldest magnetic anomaly in the Mozambique Basin to be M38.2n. These « anomalies » are flat, and do not have corresponding anomalies on the conjugate margin (Leinweber & Jokat, 2012), and may imply oceanic ridge jump in the Mozambique Basin. However, there is currently no evidence of such ridge jump in the Mozambique basin. It is worth noting that the relative distance between the conjugate anomalies M25 to their shorelines is similar (250km).

Natal Valley and Mozambique Ridge

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.*, 2016). The Mozambique ridge is formed of several bathymetric plateaus rising up to 3500 m from the ocean floor (Leinweber & Jokat, 2011), separating two Mesozoic oceanic basins that formed at different spreading regimes (the Early Cretaceous South Natal Basin and the Upper Jurassic Mozambique Sea) (Figure 11a). It has broad elevated topography on its southern half, and falls steeply into the Mozambique basin on its east.

Its origin (whether continental or oceanic) has large impact on the reconstruction of the Indian Ocean. Oceanic origin, implies its formation sometime after the breakup of Gondwana, continental origin implies otherwise. Its existence precedes the breakup.

Ben Avraham *et al.* (1995) partitioned the ridge into a northern oceanic and a southern continental crust with Moho depth of about 22km. A continental origin was however favored by Tucholke *et al.* (1981) and Hartnady *et al.* (1992), when dredged samples of Archean fragments (Tucholke *et al.*, 1981; Raillard, 1990; Mougenot *et al.*, 1991; Ben-Avraham *et al.*, 1995) were retrieved along the eastern and southern Mozambique Ridge composing of Anorthosites, Gneiss and Metagabbros (Martin *et al.* 1982). Indications of a possible oceanic origin for the ridge came from DSDP hole 249, on the southern segment (Figure 1), where MORB-like rocks were retrieved (Thompson *et al.*, 1982; Ben-Avraham *et al.*, 1995), and magnetic anomalies identification by Leinweber and Jokat, (2011). Konig and Jokat (2010) suggested oceanic origin for the Mozambique, emplaced between 140-120 Ma as a result of long lasting volcanic activity. Leinweber and Jokat (2011), propose the Mozambique Ridge to be composed of thick oceanic crust based on gravity and magnetic data. Earlier, Marks and Tikku (2001) had identified magnetics anomalies in the NNV, and suggested the area to be composed of oceanic crust. Marks and Tikku (2001) following the ideas of Martin and Hartnady (1986), proposed a model in which, Mozambique Ridge behaved as a microplate with its own independent motion between anomaly M11 and M2.

Gohl *et al.* (2011) provided seismic refraction evidence in support of the Southern Mozambique ridge having oceanic origins and possibly formed due excessive volcanism.

Fischer *et al.*, 2017, analyzing seismic reflection data observe the ridge to be compose of large number of extrusion centers, and estimated the southern Mozambique Ridge to have been emplaced between ∼131 and ∼125 Ma.

DSDP 248 and 249 (Thompson *et al.*, 1982), drilling results from the Eastern edge of the Mozambique Ridge (DSDP 248) were in the oceanic part of the Zambeze segment, and South Mozambique (DSDP 249), in the oceanic part of the Natal Valley, showing them to be composed of MORB.

However, recent expedition in the Mozambique Basin during MOZ3-5 found the North Mozambique Ridge (NMR) to consist mainly of sediments muscle on a thinned continental crust (Lepretre *et al.*, 2017). This observation is consistent with our new model we propose.

The North Natal Valley (NNV) expands between longitude 33-36°E and Latitude 25-28°S. Marks and Tikku (2001) and Tikku *et al.* (2002) identified anomaly M10 and M4 in the valley and supposing a continental origin for the Mozambique ridge proposed a rotation pole between M11 and M2 to avoid Antarctica overlapping on it. Konig and Jokat (2010) assumed oceanic origin for the Mozambique Ridge. In their model, the emplacement of the ridge occurred between 140-120Ma as a result of long lasting volcanic activity (140-120 Ma).

Leinweber and Jokat, (2012) identified SW-NE trending magnetic anomalies within the NNV and suggested it to be floored by thickened oceanic crust with the Continent Ocean Transitional (COT) lying close to the Lebombo range.

The Seismic reflection interpretations by Gohl *et al.*, (2011) and Fischer *et al.*, (2017), on the Southern Mozambique Ridge, is in agreement, and fully coherent with our new model, which proposed, following these authors, an oceanic plateau produced by the presence of a triple junction between Africa, Antarctica and the Falkland plates.

Martin *et al.* (1982) and Curtis and Hyam, (1998) however, note the Tugela ridge to mark the Continent Ocean Boundary (COB) in the NNV beyond which no continental block can be further accommodated. The seismic refractions results of PAMELA-MOZ3-5 show evidence in favor of the North Natal Valley underlain by 30-35 km thick continental crust (Lepretre *et al.*, 2017; Verrier *et al.*, 2017). Hence, following these new data, the North Natal Valley may have existed in Gondwana, and may imply the Antarctic plate cannot overlap the Valley (Figure 11b).

Consequently, on the basis of the seismic refraction evidence by Gohl *et al.* (2011) and Fischer *et al.*, (2017), we consider an oceanic origin for the South Mozambique ridge, and continental origins for the NMR and the NNV.

Maurice Ewing Bank

The Maurice Ewing Bank (MEB) represents the easternmost portion of the Falkland plateau (Figure 9). DSDP Hole 330 was bottomed in 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 PanAfrican ~650-500Ma Cape basement of Southern Africa (Thomas *et al.*, 1997; Jacobs & Thomas, 2004; Riedel *et al.*, 2013).

Reconstruction of the MEB to the southern face of the Tugela ridge is accepted by (Martin *et al.*, 1982; Goodlad *et al.*, 1982; Curtis & Hyam, 1998) as being the effective northern limit of the Natal Valley beyond which the Maurice Ewing Bank cannot be accommodated. Goodlad *et al.* (1982) and Martin *et al.* (1982) suggest the Tugela ridge to mark the COB in the Natal Valley. The current wide-angle seismic data of PAMELA-MOZ3-5 (Lepretre *et al.*, 2017) tend to support their assertion. Consequently, models moving the Falkland Plateau-MEB beyond the ridge into the NNV may not be coherent.

Aseismic Madagascar Ridge

The Madagascar Ridge is 400 km across, extending southwards from the Madagascar continent 1300 km long, with water depth between 2 and 3 km over most of the plateau. The Madagascar ridge was first considered continental extension of south of Madagascar by Heezen and Tharp, (1965). DSDP 246 and 247 attempt to determine the nature of the ridge could not reach basement due to hole instability (Schlich *et al.*, 1974). Goslin (1981) presented seismic refraction evidence in support of oceanic origin for the southern part of the ridge. They proposed a subdivision of the ridge into two distinct domains (north and south domains). Their calculation of the depth of the Moho from the seismic refraction profiles showed that the thickness of the crust varied from south to north. In the southern part of the ridge, south of 32°S, the Moho is located at 14 km (Goslin 1981). Between 32°S and 30°S, it is located at a depth of 22 to 26 km (Goslin, 1981). Their data did not extend north of 30°S, and therefore, the Moho in this area is unknown. Goslin (1981) prefer to interpret it as strongly anomalous oceanic crust. 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 spot. Goslin and Patriat (1984), consider south Madagascar ridge as conjugate to the Crozet plateau formed along the South West Indian Ridge (SWIR) between 90Ma-70 Ma (Schlich *et al.*, 1974 and Goslin, 1981).

The reconstruction models of Smith and Hallem (1970), Norton and Sclater (l979) and Sahabi (1993) leave large gap in southern Madagascar, which is filled by the northern part of the Madagascar ridge, presupposing continental origin.

4. Initial fit reconstruction (misfit between geological constraints and previous models)

Figure 12 present analysis and comparison of nine (Sahabi, 1993; Leinweber and Jokat, 2012; Torsvik *et al.*, 2012; Seton *et al.*, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2015; Nguyen *et al.*, 2016; Klimbe and Franke, 2016; Davis *et al.*, 2016) recent palinspatic models of the Indian Ocean. These models were selected to examine and compare them, to understand their geological basis. We highlight their differences and consequences on the evolution of the margins, on the basis of current geochemical and geochronological data from the basement geology, and important structural markers that we have been able to delineate on the various plates.
These models vary widely in their initial fit positions mostly occasioned by the use of different data sources and varied data interpretations. In (Konig & Jokat, 2006; Leinweber & Jokat, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2015), the model is based mainly on interpretation of magnetic profiles, and assumption of oceanic nature for the aseismic ridges (Beira High, the North Natal Valley (NNV), North Mozambique (NMR) and Madagascar Ridges, and Limpopo Basin), and hence producing overlaps across these structures and a tight fit between East and West Gondwana without considering

the specificity of each pair of conjugate passive margins. They argue the Karoo volcanism to have resulted in the final breakup of Gondwana creating oceanic crust in the Limpopo Basin and North Natal Valley (NNV), permitting overlap of the Antarctic plate across them. However, the Karoo lavas according to Riley *et al.* (2005), do not have comparable compositions to oceanic lavas or primitive plume sources. The magma also shows low $^{3}He/^{4}He$ ratios, contrary to high value for plume sources (Riley *et al.*, 2005), 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).

There is however another category of models involving the reconstruction of two to three plates. The proble*

5

m with many of such models is the least regard for the impact of the models on surrrounding plates and data constrain from other sources (Aslanian & Moulin, 2012). An example is the model by Klimbe and Franke (2016), who prefer a more southward position of Madagascar, linking the Lurio belt to the Ranotsara shear zone. We examine the impact of their model in Figure 12. The model leads to a gap of about 1000 km between Antarctica and the Zambezi coastal plain taken into cognizance current information and observations on the surruonding plates.

The position of Madagascar in Klimke and Franke (2016) presents large differences in direction, position and conjugate passive margins compared to (Sahabi, 1993; Leinweber & Jokat, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2015: Davis *et al.*, 2016). 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.*, 2015: Davis *et al.*, 2016), which seem to correlate Majunga and Lamu Basins (Leinweber and Jokat, 2012; Reeves *et al.*, 2015; Davis *et al.*, 2016), and the Morondava and Tanga-Mombasa basins (Sahabi, 1993). However, the position seems to us too tight, without any room for the passive margin, which are offshore the coastlines.

(a) Antarctica-India

Figure 13 compares the reconstruction of India-Antarctica in (Sahabi, 1993; Leinweber & Jokat, 2012; Torsvik *et al.*, 2012; Seton *et al.*, 2012; Gaina *et al.*, 2013; Reeves *et al.*, 2015; Nguyen *et al.*, 2016).

Notice Seton *et al.* (2012), Gaina *et al.* (2013), Reeves *et al.* (2015), Nguyen *et al.* (2016) misfit Archean rocks of the Napier complex and the Eastern Ghat Craton, and the conjugate Gondwanaian rifts basins. 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.

Sahabi (1993), Leinweber *et al.* (2012) and Reeves *et al.* (2015), presents a perfect alignment of Archean rocks of the Napier complex and the Ghat Craton. A good alignment of Gondwanan rifts basins and the Mesoproterozoic rocks is also achieve in these three models. Notice however, the ~450km overlap of the India plate on the Antarctica plate in Leinweber *et al.* (2012) and Reeves *et al.* (2015).

(b) India-Madagascar

Figure 14 compares the fit between Madagascar and India in the same models. In Leinweber and Jokat (2012) and Reeves *et al.* (2015), 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.

Sahabi (1993) fits the Moyar shear zone to the Batsimisaraka shear, a structure argued by Tucker *et al.* (2014) to be non-evident. Seton *et al.* (2012), Gaina *et al.* (2013) and Nguyen *et al.* (2016), on the other hand results in about ~140km gap between India and Madagascar and inaccurately fits Mesoproterozoic rocks to Archean rocks between the two plates.

(c) Consequences on Beira high, North Natal Valley and Falkland plateau

In Figure 15, we examine the consequences of these models on the Beira High continental block, the Limpopo basin, the North Natal Valley and the Falkland Plateau. All the models except Sahabi (1993) overlap on the continental Beira high (Mahanjane 2012; Mueller *et al.*, 2016), the Limpopo Basin and the North Natal Valley, based on previous indentification of magnetic anomalies across the Beira High (Leinweber et al., 2012) and the North Natal Valley (Marks and Tikku, 2001; Tikku et al., 2002; Leinweber & Jokat, 2011), which are infirm by the recent wide-angle seismic results on these structures (Mueller et al., 2016; Lepretre et al., 2017; Hanyu et al. 2017).

Notice also that all the models except Sahabi (1993) overlap the North Mozambique ridge, assuming oceanic origin.

(d) Falkland and Africa

Figure 16 presents a comparison of the fit between Falkland and Africa in Konig and Jokat (2006) and Leinweber and Jokat (2012) (orange), and Martin *et al.* (1982) and Martin and Hartnady (1986) (green).

Notice that Konig and Jokat (2006) and Leinweber and Jokat (2012) (orange) models push the Maurice Ewing Bank beyond the limit of the continental boundary (Martin et al., 1982), a boundary beyond which the Maurice Ewing Bank cannot be accommodated.

5. Geological correlation between continental results of the different plates.

(a) Antarctica-Africa- Falkland fit

Our reconstruction of Antarctica to Africa (Figure 17) was achieved on the basis of the geochronological and geochemical constraints of (Daly *et al.*, 1989; Kelly *et al.*, 2002; Dewaele, 2003; Ghosh *et al.*, 2004; Guiraud *et al.*, 2005; Jacob *et al.*, 2006; Boger, 2011; Rediel *et al.*, 2013; Rekha *et al.*, 2014) between the two plates. Recall that 1) Archean rocks of the Kaapval Craton bears strong geochemical signatures to the Greneghona Craton and therefore suggest that these two Cratons were continue 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 been situated south of Mozambique at least during the Mesoproterozoic times (Jacobs *et al.*, 2008 and Rediel *et al.*, 2013). We align the two boundary faults of Archean Kaapval and Grunneghona Cratons (Tankard *et al.*, 2009) and their Mesoproterozoic orogenic zones. The data is further strengthened by the new information from seismic refraction in the Limpopo Basin and the NNV (Domingues *et al.*, 2016; Lepretre *et al.*, 2017; Verrier *et al.*, 2017), and on the Beira High (Mueller *et al.*, 2016) which invalidate overlap of Antarctica on these structures.

Our reconstruction of the Falkland-MEB and Southern Africa was achieved along the lines of (Curtis and Hyam, 1998; Marshall, 1994; Martin *et al.*, 1982, 1982; Lock, 1978) (Figure 17). The main problem regarding the reconstruction of the Patagonia-Falkland with respect to Africa due 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 (Zaffarana *et al.*, 2010). Currently, the amount of displacement, and the timing of the deformation remains a subject of debate.

Rapela *et al.*, (1991) suggested the regional structure to indicate NW-SE dextral strike-slip displacement without evidence of regional extension. Franzese and Martino (1998) contradicted Rapela *et al.*, (1991) suggesting mainly oblique reverse deformation. Based on field observation 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 major dextral fault system. Hence, the reconstruction of the Patagonia-Falkland requires no dextral strike slip deformation along the Gastre Fault System.

However, with the new seismic refraction results from Lepretre et al., (2017), 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 ~250km of strike-slip deformation along the GFS to firmly close the South Natal Valley.

(b) Antarctica-India fit

We reconstruct Antarctica and India (Figure 18) on the basis of the geochronological data of (Fitzsimons, 2000; Kelly *et al.*, 2002: Ghosh *et al.*, 2004; Biswal & Sinha, 2004; Boger, 2011). Recall that rocks of the Eastern Ghats Craton and the Rayner - Napier complexes share similar geochronogical properties (Biswal & Sinha, 2004, and Ghosh *et al.*, 2004; Boger, 2011), and the Rayner Complex extends from Enderby Land into the Mesoproterozoic rocks of the Eastern Ghats Granulite in India. Their juxtaposition is further strengthen by the continuity of Gondwanan rift basins of Godavari and

Mahanadi (India), and Lambert and Robert rift valleys of Eastern Antarctica (Kelly *et al.*, 2002; Ghosh *et al.*, 2004: Biswal & Sinha, 2004). The ~120km overlap between India and Antarctica within Southern Bangladeshis explained by the not clearly defined limits of the India plate within the region, and the characterization of the region by Large compressional deformation.

(c) Antarctica-Australia fit

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

(e) Madagascar-Africa fit

Our model for Madagascar and Africa (Figure 20), on the basis of similar ages, 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 continue the Brava fault in Kenya with the Andreaparaty shear zone in Madagascar. This allows the Belet Uen fault to be fitted to the fault lying to 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. 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 Abdullah, 1995). The fit also allows a good view of the extent of the Neoproterozoic granulites, of Madagascar (Vohibory domain) and Africa (The Cabo Delgado nappes of the Mozambique belt) (Bingen *et al.*, 2009 and Tucker *et al.*, 2014), which share similar geochemical properties. 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 early Ediacaran time (0.65– 0.63 Ga; Tucker *et al.*, 2014). Recall also that the protolith of the Bur Acaba share similar geochemical and geochronological properties with the Late Archean rocks of the Antananarivo Domain (2.75-2.50 Ga) (Tucker *et al.*, 2014) and may therefore suggest that the Bur Acaba may have been continues with the Dharwar Craton before Gondwana's breakup.

(e) Madagascar-India fit

Our reconstruction between Madagascar and India (Figure 21) is along the lines of Windley (1994), Rekha *et al.* (2014) and Tucker *et al.* (2014) who provided geological evidence for the continuation of Dharwar Craton between India and Madagascar. The Western Dharwar Archean Craton and a number of Precambrian structures can be traced from Indian into Eastern Madagascar. The Archean rocks of Antongil and Fenoarivo in Madagascar is surrounded by Neoarchean and Paleoproterozoic rocks from the eastern margin into Antananarivo. This permits a trace of the Archean basement rocks in Madagascar, which is juxtapose to its conjugate Eastern Dharwar basement in India. We trace the Ranotsara shear to the Karrur Kambam shear zone in India (Rekha *et al.*, 2014), and 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). 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 (Figure 21). The reconstruction leads to 100km overlap between India and Africa. This is due to the poorly defined limits of the India plate in the Karachi area.

6. Proposed model of Gondwana's initial fit

Our proposed initial fit of Gondwana 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.

The 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 (Kuster *et al.*, 1990; Lenoir *et al.*, 1994 and Tucker *et al.*, 2014) (Figure 23).

It aligns accurately, the Precambrian shear zones of the Agavo Ifadiana and Ranostara of Madagascar to the Palghat and Karrur Kambam shear zones of India respectively (Figures 22 and 23).

It also allows the full extent of the PanAfrican orogenic event and the Karoo volcanism in Africa and Antarctica, and perfectly aligns Archean and Mesoproterozoic rocks in Madagascar and India (Figure 24).

With regard to the fit between Australia and Antarctica, it permits a continuation of the Beardmore and Mawson Cratons in Antarctica into Australia, and continues trace of Mesoproretozoic A (1.65-1.55Ga), Mesoproretozoic D (1.35-1.15Ga), Mesoproretozoic E (1.1-1.05Ga), between Antarctica and Australia.

In fitting India to Antarctica, our model achieves a good alignment of Archean rocks of the Napier complex and the Eastern Ghat Craton, as well as the alignment of conjugate Gondwanan rifts basins (Mahanadi and Gondavari of India, and Lambert and Enderby rift basin of Antarctica) and Mesoproterozoic rocks between the two plates.

Notice the alignment of the Vohibory PanAfrican shear zone to the PanAfrican shear zone in Tanzania. The Brava faults in Kenya is fitted to the Andreaparaty shear zone in Madagascar, and the Belet Uen fault in Somalia fitted to the fault lying to the northern border of Madagascar.

The Ranotsara shear zone is proposed to continue with the Tombo faults due to their perfect alignment and NW-SW trend, and may continue into Kenya into the Aswa shear zone.

The extent of the Neoproterozoic granulites (0.65– 0.63 Ga Bingen *et al.*, 2009: Tucker *et al.*, 2014) in Mozambique and Madagascar is also evident in our model.

6.1 Model consequence on offshore geological structures

The model is coherent with current geophysical and geological data interpretations on 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.*, 2005; Gohl *et al.*, 2011; Fischer et al., 2017), continental origin for the North Natal Valley and North Mozambique ridge (Martin *et al.*, 1982; Curtis & Hyam, 1998; Lepretre *et al.*, 2017; Verrier *et al.*, 2017), 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 and Goslin, 1981), and seismic reflection result 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

The new model apart from providing a better constraining of Gondwana's initial fit on the basis of published geochronological data and delineated structural markers, also provides a perfect fitting of conjugate basins of the various plates. Notice the alignment of the Karoo sediments of Madagascar and Africa, and the extent of the Karoo and Ferrar volcanism in Africa and Antarctica (Duncan *et al.*, 1997: Jourdan *et al.*, 2005; Klausen, 2009) (Figure 24).

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. This allows for the eastern margin of Karoo rocks mapped in SW Madagascar to be aligned with similar rocks in the Selous-Rufuji-Tanga Basins in Tanzania which is continued northeastward into the Lamu-Majunga conjugate Karoo basins to link the Tethyan rifts of peri Arabia-India.

A line of deep-seated intrusions across the NE terminus of the Selous and Rufuji basins is well seen on the satellite gravity data of Sandwell *et al.* (2014), and was interpreted by (Reeves, 2014) to indicate the initial line of fracture of Madagascar away from the Africa continent. Reconstructions along this line allows 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 it conjugate Zambezi basin on the basis of identified magnetic anomalies and fracture zones (Segoufin, 1978; Simpson *et al.*, 1979; Konig & Jokat, 2010; Leinweber *et al.*, 2012)

Between Antarctica and India, the Bengal basin of India is fitted to 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. Conclusion

In this study, we presented analysis of current reconstruction models of the Indian Ocean to examine their consequences and underlying reasons. These models present a number of gaps, overlaps and misfit of major structural and Cratonic bodies, and raises critical scientific questions in their full-fit reconstruction. We undertake study of onshore and offshore geological and geophysical data published and newly acquired within the framework of the PAMELA project to produce a more holistic model of Gondwana's initial fit. Our model is coherent and respect current knowledge we have about 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. The model in agreement with Muller et al., (2016) on the continental origin of the Beira High allows adequate space for its accommodation. The model is further coherent with the continental origin interpretation of the Beira High, and seismic refraction interpretation of Pamela MOZ3-5 of the Northern Mozambique Ridge, and Northern Natal Valley confirming these areas to be underlained by continental crust.

Acknowledgement

This study was co-funded by TOTAL and Ifremer as part of the PAMELA (Passive Margin Exploration Laboratories) scientific project, led by Jean-François Bourillet (Ifremer) and Philippe Bourges, Jean-Noel Ferry and Jacques Durand (Total). The work was conducted in the Geodynamics and Sedimentary Laboratory of Ifremer, Geosciences Department of the Université de Rennes 1 and TOTAL Pau. We thank all participants in the PAMELA project. Our special thanks goes to Pascal Pelleau for his assistance with the Placa software and Sylvain Bermell for his help with Arcgis 10.2. The results are based on the PhD thesis of Joseph Offei Thompson which was co-funded by TOTAL and IFREMER as part of the PAMELA (Passive Margin Exploration Laboratories) scientific project.

REFERENCES

Aslanian D. and Moulin M., 2012. Paleogeographic consequences of conservational models in the South 269 Atlantic Ocean, In: Mohriak, W.U., Danforth, A., Post, P.J., Brown, D.E., Tari, G.C., Nemcok, M. and 270 Sinha, S.T. (Eds). Conjugate Divergent Margins. *Geological Society, London, Special Publications,* 369, 271 http://dx.doi.org/10.1144/SP369.5.

Aslanian, D., Moulin, M., Olivet, J.-L., Unternehr, P., Matias, L.., Bache, F., Rabineau, M., Nouzé, H., Klingelhoefer, F., Contrucci, I., Labails, C., 2009. Brazilian and African passive margins of the Central Segment of the South Atlantic Ocean: kinematic constraints. *Tectonophysics*, 468, 98–112.

Ben-Avraham, Z., Hartnady, C.J.H. and le Roex, A.P., 1995. Neotectonic activity on continental fragments in the Southwest Indian Ocean: Agulhas Plateau and Mozambique Ridge, *J. Geophys. Res.*, 100, 6199–6211.

Bernard, A., Munschy, M., Rotstein, Y., Sauter, D., 2005. Refined spreading history at the Southwest Indian Ridge for the last 96 Ma, with the aid of satellite gravity data. *Geophysical Journal International*, 162, 765–778.

Besairie, H., Collignon, M., 1972. Geologie de Madagascar; I, Les terraines sedimentaires. *Annales Geol.* Madagascar 35, 463.

Bingen B., Jacobs J., Viola G., Henderson I.H.C., Skår Q., Boyd R., Thomas R.J., Solli A., Key R.M., Daudi E.X.F., 2009. Geochronology of the Precambrian crust in the Mozambique belt in NE Mozambique, and implications for Gondwana assembly. Precambrian Research, 170, 231–255.

Biswal, T.K. and Sinha, S., 2004. Fold-Thrust-Belt Structure of the Proterozoic Eastern Ghats Mobile Belt: A Proposed Correlation between India and Antarctica in Gondwana. *Gondwana Research*, 7, I, 43-56.

Boger, D.S., 2011. Before and After Gondwana. *Gondwana Research*, 19, 335-371.

Bordy, E.M. and Catuneanu, O., 2001. Sedimentology of the upper Karoo fluvial strata in the Tuli Basin, South Africa. *Journal of African Earth Sciences,* 33, 605-629.

Borg, S.G. and DePaolo, D.J., 1991. A tectonic model of the Antarctic Gondwana margin with implications for southeastern Australia: isotopic and geochemical evidence. *Tectonophysics,* 196, 339-358.

Bristow. J.W., 1980. The geochronology and geochemistry of Karoo volcanics in the Lebombo and adjacent areas. Department of Geochemistry, University of Cape Town. http://hdl.handle.net/11427/12534.

Catuneanu, O., 2004. Basement control on flexural profiles and the distribution of foreland facies: The Dwyka Group of the Karoo Basin, South Africa. *Geological Society of America* 32, 6. 517–520; doi: 10.1130/G20526.1.

Cande, S. C. and Mutter, J. C., 1982. A revised identification of the oldest sea-floor spreading anomalies between Australia and Antartica. *Earth Planet. Sci. Lett.,* 58, 151-160.

Chetty, P., and Green, R. E., 1977. Seismic refraction observations in the Transkei Basin and adjacent areas, Mar. *Geophys. Res.*, 3, 197–208.

Collins, A.S., Windley, B.F., 2002. The tectonic evolution of central and northern Madagascar and its place in the final assembly of Gondwana. *J. Geol.* 110, 325–339.

Collins, A.S. and Pisarevsky, S.A. 2005. Amalgamating eastern Gondwana: the evolution of the Circum-Indian Orogens. *Earth Science Reviews*, 71, 229–270.

Courrier, P. and Lafont, M., 1987. Mise au point sedimento-structurale et petroliere du bassin de morondava. Societé nationale Elf aquitaine (production).

Cox, G.M., Lewis, C.J., Collins, A.S,, Halverson, G.P., Jourdan, F., Foden, J., Nettle, D., Kattan, F., 2012. Ediacaran terrane accretion within the Arabian–Nubian Shield. *Gondwana Research*, 21, 341–352.

Curtis, M. L. and Hyam, D. M., 1998. Late Palaeozoic to Mesozoic structural evolution of the Falkland Islands: a displaced segment of the Cape Fold Belt. *Journal of the Geological Society*, London, 155, 115–129.

Dasgupta, S. Bose, S., Das, K., 2013. Tectonic evolution of the Eastern Ghats Belt, India. *Precambrian Research*, 227, 247–258.

Daly, M.C., Chorowicz, J. and Fairhead, J.D., 1989. Rift basin evolution in Africa: the influence of reactivated steep basement shear zones. In: Inversion tectonics (Edited by Cooper, M.A. and Wiuiams, G.D.), *Geological Society London Special Publication*, 44, 309-334.

Davis, J.K., Lawver, L.A, Norton, I.O., Gahagan, L.M., 2016. New Somali Basin magnetic anomalies and a plate model for the early Indian Ocean. *Gondwana Research*, 34, 16–28.

Dewaele, B., Fitzsimons, I.C.W., Wingate, M.T.D., Mapani, B.S.E., 2003. The tectonothermal history of the Irumide belt of Zambia. Regional Significance of New Geochronological Constraints, Assembly and Breakup of Rodinia, South China Field Symposium, Hangzhou, China, 16 – 18.

De Wit, M.J., 2003. Madagascar: Heads it's a Continent, Tails It's an Island. *Annu. Rev. Earth Planet. Sci*., 31, 213–48.

Dingle and Scrutton, 1974. Continental breakup and the development of post-Paleozoic sedimentary basins around southern Africa. Geol. Soc. Am. Bull., 85, 1467–1474

Domingues, A., Silveira, G., Ferreira, A. M.G., Chang, S., Custodio, S., Fonseca, J. F.B.D., 2016. Ambient noise tomography of the East African Rift in Mozambique. *Geophys. J. Int*., 204, 1565–1578.

Duncan, R.A., Hooper, P.R., Rehacek, J., Marsh, J.S., Duncan, A.R., 1997. The timing and duration of the Karoo igneous event, southern Gondwana. *J. Geophys. Res.*, 102, 18127–18138. http://dx.doi.org/10.1029/97JB00972.

Eagles, G., König, M., 2008. A model of plate kinematics in Gondwana breakup. *Geophysical Journal International*, 173, 703–717.

Elliot, D.H., Fleming, T.H., 2000. Weddell triple junction: the principal focus of Ferrar and Karoo magmatism during initial breakup of Gondwana. *Geology*, 28, 6, 539–542.

Elliot, D.H., Fleming, T.H., 2004. Occurrence and dispersal of magmas in the Jurassic Ferrar Large Igneous Province, Antarctica. *Gondwana Research*, 7, 223–237.

Fischer, M.D., Uenzelmann-Neben, G, Jacques, G., Werner, R., 2017. The Mozambique Ridge: a document of massive multistage magmatism. *Geophys. J. Int*. 208, 449–467.

Flores, G., 1964. On the age of the Lupata rocks, lower Zambezi River, Mozambique. *Trans. Geol. Soc. S. Afr*. 67 p1ll—118.

Flores, G., 1970. Suggested origin of the Mozambique Channel. *Trans. Geol. Soc. South Afr*.

Flores, G., 1973. The Cretaceous and Tertiary basins of Mozambique and Zululand. Ass. Afr. Geol. Surveys in Symp of East Afr. Coast. Basins Paris.

Foster, D.A, Goscombe, B. D., Newstead, B., Mapani, B., Mueller, P.A, Gregory, L.C, Muvangua, E., 2015. U–Pb age and Lu–Hf isotopic data of detrital zircons from the Neoproterozoic Damara Sequence: Implications for Congo and Kalahari before Gondwana. *Gondwana Research,* 28, 179–190.

Franzese, J., Martino, R., 1998. Aspectos cinema´ticos y tecto´nicos de la zona de cizalla de Gastre en la Sierra de Calcatapul, Provincia de Chubut; Argentina. X Congreso Latinoamericano de Geologı´a y VI Congreso Nacional de Geologı´a Econo´mica (Buenos Aires), Actas II, 3.

Fitzsimons, I.C.W., 2000. Grenville-age basement provinces in East Antarctica: Evidence for three separate collisional orogens. Tectonics Special Research Centre, School of Applied Geology, Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia.

Gaina, C., Müller, R.D. Brown, B. and Ishihara, T., 2007. Breakup and early seafloor spreading between India and Antarctica, *Geophys. J. Int.*, 170, 151–169, doi:10.1111/j.1365-246X.2007.03450.x.

Gaina, C., Torsvik, T., Van Hinsbergen, D., Medvedev, S., Werner, S. and Labails, C., 2013. The African Plate: A history of oceanic crust accretion and subduction since the Jurassic. *Tectonophysics*, 604, 4-25, doi: 10.1016/j.tecto.2013.05.037

Gaina, C., Van Hinsbergen, D.J.J. and Spakman, W., 2015. Tectonic interactions between India and Arabia since the Jurassic reconstructed from marine geophysics, ophiolite geology, and seismic tomography. *Tectonics,* 34, 875–906. Doi:10.1002/2014TC003780.

Geiger, M., Clark, D.N. and Mette, W., 2004. Reappraisal of the timing of the breakup of Gondwana based on sedimentological and seismic evidence from the Morondava Basin, Madagascar. *Journal of African Earth Sciences*, 38, 363-381.

Ghosh, J.G., De Wit, M.J., Zartman, R.E., 2004. Age and tectonic evolution of Neoproterozoic ductile shear zones in the Southern Granulite Terrain of India, with implications for Gondwana studies. *Tectonics*,. 23, TC3006, doi:10.1029/2002TC001444, 2004.

Gnos, E., Immenhauser, A., Peters, T., 1997. Late Cretaceous/early Tertiary convergence between the Indian and Arabian plates recorded in ophiolites and related sediments. *Tectonophysics,* 271, 1-19.

Gohl, K., Uenzelmann-Neben, G., Grobys, N., 2011. Growth and dispersal of a Southeast African large igneous province. *S. Afr. J. Geol.,* 114, 379–386, doi.org/10.2113/gssajg.114.3-4.379.

Goodlad, S.W., Martin, A.K., Hartnady, C.J.H., 1982. Mesozoic magnetic anomalies in the southern Natal Valley. *Nature*, 295, 686–688, doi.org/10.1038/295686a0.

Gosena, V., Loske, W., 2004. Tectonic history of the Calcatapul Formation, Chubut province, Argentina, and the "Gastre fault system". *Journal of South American Earth Sciences,* 18, 73–88.

Goslin. J., 1981. Etude geophysique des reliefs asismiques de l'Ocean Indien occidental et austral, Thése d'Etat, UniversitC Louis-Pasteur. Strasbourg, 267 pp.

Goslin. J. and Patriat. P., 1984. .Ahsolute and relative plate motions and hypotheses on the origin of five aseismic ridges in the Indian Ocean. *Tectonophysics,* 101, 221.-244.

Guillocheau, F., Liget, A., 2009. Bases de données paléogéographiques en Afrique permien terminal jurassique inférieur etude des bassins "karoo". Géociences-Rennes Université de Rennes 1 / CNRS (UMR 6118).

Greenway, M.E., 1972. Geology of the Falkland Islands. Department of geology, University of Birmingham.

Guiraud, R., Bosworth, W., Thierry, J., Delplanque, A., 2005. Phanerozoic geological evolution of Northern and Central Africa: An overview. *Journal of African Earth Sciences,* 43, 83–143.

Hanyu, T., Nogi, Y., Fujii, F., 2017. Crustal formation and evolution processes in the Natal Valley and Mozambique Ridge, off South Africa. Polar Science, 13, 66-81.

Hartnady, C.J.H., Ben-Avraham, Z. and Rogers, J., 1992. Deep-ocean basins and submarine rises off the continental-margin of South-eastern Africa: new geological research, *S. Afr. J. Sci.,* 88, 534–539.

Hastie, W.W., Watkeys, M.K. and Aubourg, C. 2014. Magma flow in dyke swarms of the Karoo LIP: implications for the mantle plume hypothesis. *Gondwana Research*, 25, 736–755.

Heezen, B.C., and M. Tharp., 1965. Physiographic Diagram of the Indian Ocean the Red Sea the South China Sea the Sulu Sea and the Celebes Sea, *Geological Society of America*, New York, 1965.

Jacobs, J., Pisarevsky, S., Thomas, R.J., Becker, T., 2008. The Kalahari Craton during the assembly and dispersal of Rodinia. *Precambrian Research,* 160, 142–158.

Jacobs, J., Thomas, R.J., 2004. Himalayan-type indenter-escape tectonics model for the southern part of the Neoproterozoic–early Paleozoic East African–Antarctic orogen. *Geology*, 32, 721–724.

Jacobs, J., Bauer, W., Fanning, C.M., 2003. Late Neoproterozoic/Early Palaeozoic events in central Dronning Maud Land and significance for the southern extension of the East African Orogen into East Antarctica. *Precambrian Research*, 126, 27–53.

Jacobs, J., Fanning, C.M., Henjes-Kunst, F., Olesch, M., Paech, H., 1998. Continuation of the Mozambique Belt into East Antarctica: Grenville-age metamorphism and polyphase PanAfrican high-grade events in central Dronning Maud Land. *Journal of Geology*, 106, 385–406.

Jokat, W., Boebel, T., König, M., Meyer, U., 2003. Timing and geometry of the early Gondwana breakup. *Journal of Geophysical Research*, 108 (B9), 1–15.

Jourdan, F., Féraud, G., Bertrand, H., Kampunzu, A.B., Tshoso, G., Watkeys, M.K., Le Gall, B., 2005. Karoo large igneous province: brevity, origin, and relation to mass extinction questioned by new 40Ar/39Ar age data. *Geology*, 33, 745–748.

Jourdan, F., Féraud, G., Bertrand, H., Watkeys, M.K. and Renne, P.R., 2007. Distinct brief major events in the Karoo large igneous province clarified by new 40Ar/39Ar ages on the Lesotho basalts. *Lithos*, 98, 195-209.

Kazmin, V.G., (1991). Collision and rifting in the history of the Tethys ocean. Geotektonika, 5, 14-23. *Tectonophysics*, 196, 371-384.

Klausen, M.B., 2009. The Lebombo monocline and associated feeder dyke swarm: diagnostic of a successful and highly volcanic rifted margin? *Tectonophysics*, 268, 42–62.

Klimke, J., Franke, D., 2016. Gondwana breakup: no evidence for a Davie Fracture Zone offshore northern Mozambique, Tanzania and Kenya. Terra Nova, 28, 4, 233–244.

Kelly, N.M., Clarke, G.L., Fanning, C.M., 2002. A two-stage evolution of the Neoproterozoic Rayner Structural Episode: new U–Pb sensitive high resolution ion microprobe constraints from the Oygarden Group, Kemp Land, East Antarctica. *Precambrian Research*, 116, 307–330.

König, M., Jokat, W., 2006. The Mesozoic breakup of the Weddell Sea. *Journal of Geophysical Research*, 111, B12102, doi:10.1029/2005JB004035.

König, M., Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potentialfield data. *Geophysical Journal International,* 180 (1), 158–180.

Kuster, D., Utke, A., Leupolt, L., Lenoir, J.L., Haider, A., 1990. PanAfrican granitoid magmatism in northeastern and southern Somalia. Berliner Geowissenschaftliche Abhandlungen 120, 519 – 536.

Labails, C., Olivet, J.L., Aslanian, D. and Roest, W.R., 2010. An alternative early opening scenario for the Central Atlantic Ocean, Earth planet. *Earth and Planetary Science Letters*, 297, 355–368.

Leinweber, V., Klingelhoefer, F., Neben, S., Reichert, C., Aslanian, D., Matias, L., Heyde, I., Schreckenberger, B. and Jokat, W., 2012. The crustal structure of the central Mozambique continental margin —wide-angle seismic, gravity and magnetic study in the Mozambique Channel, Eastern Africa. *Tectonophysics*, 599, 170-196.

Leinweber, V.T., Jokat, W., 2012. The Jurassic history of the Africa-Antarctica corridor—new constraints from magnetic data on the conjugate continental margins. *Tectonophysics*, 530-531, 87–101. http://dx.doi.org/10.1016/j.tecto.2011.11.008.

Leinweber, V.T., Jokat, W., 2011. Is there continental crust underneath the Northern Natal Valley and the Mozambique Coastal Plains? *Geophysical Research Letters*, 38, L14303.

Lenoir, J.L., Légois, J.P., Theuninissen, K., Klerkx, J., 1994. The Palaeoproterozoic Ubendian shear belt in Tanzania: geochronology and structure. *Journal of African Earth Sciences*, 19, 3, 169-184.

Lepretre, A., Fanny, V., Evain, M., Schnurle, P., Watremez, L, Aslanian, D., De Clarens, P., Afonso, N., Afilhado, A. Leroy, d'Acremont, E,, Castilla, R., Moulin, M., First results on the crustal structure of the Natal Valley from combined wide-angle and reflection seismic data (MOZ3/5 cruise), South Mozambique Margin. EGU 2017 Poster.

Lock, B.E. 1978. The Cape Fold Belt of South Africa; tectonic control of sedimentation. Proc. Geol. Ass., 89(1). 263-281.

Lorenzo, J.M., Mutter, J.C., 1988. Seismic stratigraphy and tectonic evolution of the Falkland/Malvinas Plateau. Lamont-Doherty Geological Observatory of Columbia University. Palisades, New York 10964-0190, U.S.A.

Mahanjane, E.S., 2012. A geotectonic history of the northern Mozambique Basin including the Beira High—A contribution for the understanding of its development. Mar. Pet. Geol., 36, 1–12. http://dx.doi.org/10.1016/j.marpetgeo.2012.05.007.

Marks, K.M. and Tikku, A.A., 2001. Cretaceous reconstructions of East Antarctica, Africa and Madagascar. *Earth and Planetary Science Letters*, 186, 479-495

Martin, A.K., Hartnady, C. J. H., 1986. Plate tectonic development of the South West Indian Ocean: a revised reconstruction of East Antarctica and Africa. *Journal of Geophysical Research*, 91, 4767–4786.

Martin, A.K., Goodlad, S.W., Hartnady, C. J. H., Du Plessis, A., 1982. Cretaceous palaeo-positions of the Falkland Plateau relative to southern Africa using Mesozoic seafloor spreading anomalies. *Geophysical Journal of the Royal Astronomical Society*, 71, 567–579.

Marshall, J.E., 1994. The Falkland Islands: a key element in Gondwana paleogeography. *Tectonophysics*, 13, 499–514.

Matias, L.M., Olivet, J.-L., Aslanian, D., Fidalgo González, L., 2005. PLACA: a white box for plate reconstruction and best-fit pole determination. *Computers and Geosciences*, 31, 437–452.

McKenzie, D., Sclater, J.G, 1971. The Evolution of the Indian Ocean since the Late Cretaceous. *Geophys. J. R.* usfr. Soc., 25,437-528.

Melluso, L., Cucciniello, C., Petrone, C.M., Lustrino, M., Morra, V., Tiepolo, M., Vasconcelos, L., 2008. Petrology of Karoo volcanic rocks in the southern Lebombo monocline, Mozambique. *J. African Earth Sci*. 52, 139–151.

Mougenot, D., Gennesseaux, M., Hernandez, J., Lepvrier, C., Malod, J.A., Raillard, S., Vanney, J.R. and Villeneuve, M., 1991. The Mozambique Ridge (Indian-Ocean)—a continental fragment shaped during the transform motion of American and Antarctic plates along East-Africa, C. R. Acad. Sci., Paris II, 312, 655–662.

Moulin, M., Aslanian, D., Unternehr, P., 2010. A new starting point for the South and Equatorial Atlantic Ocean. *Earth-Science Reviews*, 98, 1–37.

Moulin, M., Aslanian, D., 2016. PAMELA-MOZ03 cruise, RV Pourquoi pas ?, http://dx.doi.org/10.17600/16001600.

Moulin, M., Evain, M., 2016. PAMELA-MOZ05 cruise, RV Pourquoi pas ?, http://dx.doi.org/10.17600/16009500.

Mueller, C.O., Jokat, W. and Schreckenberger, B., 2016. The crustal structure of Beira High, central Mozambique—Combined investigation of wide-angle seismic and potential field data. *Tectonophysics*, 683, 233-254.

Mueller, C.O., Jokat, W., 2017. Geophysical evidence for the crustal variation and distribution of magmatism along the central coast of Mozambique. *Tectonophysics*. S0040-1951(17)30253-6. doi: 10.1016/j.tecto.2017.06.007.

Muller, R.D., Roest, W. R., Royer, J.Y., Gahagan, L.M .and Sclater, J.G., 1997. Digital isochrons of the world's ocean floor, *J. Geophys. Res.*, 102, 3211– 3214.

Nguyen, L.C., Hall, S.A., Bird, D.E., Ball, P.J., 2016. Reconstruction of the East Africa and Antarctica continental margins. *J. Geophys. Res*. Solid Earth, 121, 4156–4179. doi:10.1002/2015JB012776

Norton, I.O., Sclater, J.G., 1979. A model for the evolution of the Indian Ocean and the breakup of Gondwanaland. *Journal of Geophysical Research*, 84, 6803–6830.

Powells, C., Johnson, B.D., Veevers, J. J., 1980. A revised fit of east and west Gondwanaland. *Tectonophysics*, 63, 13-29.

Rapela, C.W., Dias, G.F., Franzese, J.R., Alonso, G., Benvenuto, A.R., 1991. El Batolito de la Patagonia central: evidencias de un magmatismo triásico-jurásico asociado a fallas transcurrentes. Revista Geológica de Chile, 18 (2), 121-138.

Rasoamalala, V., Salvi, S., Béziat D., Ursule, P., Cuney, M., de Parseval Ph., Guillaume, D., Moine, B., Andriamampihantona, J., 2014. Geology of bastnaesite and monazite deposits in the Ambatofinandrahana area, central part of Madagascar: An overview. *Journal of African Earth Sciences*, 94, 128–140.

Rajaprian, K., Singh, K., Vinoth, M., Kumar, V., Kumar, R. S., 2014. Metamorphism and deformation of mafic and felsic rocks in Bhavani Shear Zone, Tamilnadu, India. *International Journal of Advanced Geosciences*, 2, 1, 13-19.

Raillard, S., 1990. Les marges de l'Afrique de l'Est et les zones de fracture associées: Chaine Davie et Ride du Mozambique, Ph.D. thesis, Laboratoire de Géodynamique sous-marine Villefranche-sur-mer et Département de Géologie Océanique Paris, Université Pierre et Marie Curie.

Rekha, S., Bhattacharya, A., Chatterjee N., 2014. Tectonic restoration of the Precambrian crystalline rocks along the west coast of India: Correlation with eastern Madagascar in East Gondwana. *Precambrian Research*, 252, 191–208.

Reeves, C.V. 2000. The geophysical mapping of Mesozoic dyke swarms in southern Africa and their origin in the disruption of Gondwana. *Journal of African Earth Sciences*, 30, 499– 513.

Reeves, C., De Wit, M., 2000. Making ends meet in Gondwana: retracing the transforms of the Indian Ocean and reconnecting continental shear zones. *Terra Nova*, 12, 272–280.

Reeves, C., Mahanjane, E.S. (2013) Mozambique and its role in the downfall of Gondwana. Geological Society of Houston/Petroleum Exploration Society of Great Britain, 11– 12 September 2013, London.

Reeves, C., 2014. The position of Madagascar within Gondwana and its movements during Gondwana dispersal. *Journal of African Earth Science*, 94, 45-57.

Reeves, C., Teasdale, J.P. and Mahanjane, E.S., 2015. Insight into the Eastern Margin of Africa from a new tectonic model of the Indian Ocean. In Nemcok, M., Rybar, S., Sinha, S.T., Hermeston, S.A. and Ledvényiova , L. (eds), Transform Margins: Development, Controls and Petroleum Systems. Geological 256 Society, London, Special Publications, 431, http://doi.org/10.1144/SP431.12.

Reeves, C.V., Teasdale, J.P., and Mahanjane, E.S., 2016. Insight into the Eastern Margin of Africa from a new tectonic model of the Indian Ocean. Geological Society, London, *Special Publications*, 431, http://doi.org/10.1144/SP431.12.

Riedel, S. Jacobs, J. Jokat, W., 2013. Interpretation of new regional aeromagnetic data over Dronning Maud Land (East Antarctica). *Tectonophysics*, 585, 161–171.

Riley, T.R., Leat, P.T., Curtis, M.L., Millar, L.L., Fazel, A., 2005. Early-Middle Jurassic dolerite dykes from western Dronning Maud Land (Antarctica): identifying mantle sources in the Karoo large igneous province. *Journal of Petrology*, 46, 1489–1524.

Salman, G., Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sediment. *Geology*., 96, 7–41. http://dx.doi.org/10.1016/0037-0738(95)00125-R.

Sahabi, M. 1993. Modèle général de l'évolution de l'océan Indien. Brest, Univ. De Bretagne Occidentale: 187 p vol. 1 et 243 p vol. 2.

Sahabi, M., Aslanian, D., Olivet, J.-L., 2004. Un nouveau point de départ pour l'histoire de l'Atlantique Central. *Compte Rendus Geosciences*, 33, 1041–1052

Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E., Francis, R., 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science*, 346, 65–67

Schlich, R., Simpson, E.S.W., Gieskes, J., Girdley, W.A., Leclaire, L., Marshall, B.V., Moore, C., Muller, C., Sigal, J., Valuer, T.L., White, S.M. and Zobel, B., 1974. DSDP Site 241, Initial report of the Deep Sea Drilling Project. Washington DC, 87-138.

Segoufin, J., 1978. Anomalies magnétiques mésozoïque dans le bassin de Mozambique. Comptes Rendus de l'Académie des Sciences Paris, Série D t. 287, 109–112.

Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shepard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S. and Chandler, M., 2012. Global continental and ocean basin reconstructions since 200 Ma. *Earth-Science Reviews*, 113, 212-270.

Simpson, E.S.W., Sclater, J.G., Parsons, B., Nortion, I.O., Meinke, L., 1979. Mesozoic mag-netic lineations in the Mozambique basin. *Earth and Planetary Science Letters*, 43, 260–264.

Smith, A.G. and Hallam, A., 1970. The fit of the southern continents. *Nature*, 225, 130 -144.

Svensen, H., Corfu, F., Polteau, S., Hammer, Ø., Planke, S. 2012. Rapid magma emplacement in the Karoo Large Igneous Province. Earth and Planetary Science Letters 325–326, 1–9.

Tankard, A., Welsink, H., Aukes, P., Newton, R., Stettler, E., 2009. Tectonic evolution of the Cape and Karoo basins of South Africa. *Marine and Petroleum Geology*, 26, 1379–1412.

Tarling, D.H., 1972. Another Gondwanaland. Nature, 238: 92-93.

Thomas, R.J., Agenbacht, A.L.D., Cornell, D.H., Moore, J.M., 1994. The Kibaran of southern Africa: tectonic evolution and metallogeny. Ore Geol. Rev., 9, 131–160.

Thomas, R.J., Jacobs, J., Weber, K., 1997. Geology of the Mesoproterozoic Cape Meredith Complex, West Falkland. In: Ricci, C.A. (Ed.), The Antarctic Region: Geological Evolution and Processes. *Terra Antarctica Publication*, Siena, 21–30.

Thompson, G., Bryan, W.B., Frey, F.A., Dickey, J.S. and Davies, H., 1982. Petrology, geochemistry and original tectonic setting of basalts from the Mozambique Basin and Ridge (DSDP Sites 248, 249 and 250), and from the Southwest Indian Ridge (DSDP Site 251), Mar. *Geol.*, 48, 175–195.

Tikku, A.A., Karen M. Marks, K.M., Kovacs, L.C., 2002. An Early Cretaceous extinct spreading center in the northern Natal valley. *Tectonophysics*, 347, 87–108.

Torsvik, T., Müller, R.D., Van der Voo, R., Steinberger, B. and Gaina, C., 2008. Global plate motion frames: toward a unified model, *Reviews of Geophysics*, 46, 1-44

Torsvik, T., Van der Voo , R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P. V., van Hinsbergen, D.J.J., Domeier, M., Gaina, C., Tohver, E., Meert, J.G., McCausland, P.J.A. and Cocks, L.R.M., 2012. Phanerozoic polar wander, palaeogeography and dynamics. *Earth-Science reviews*, 114, 328-365.

Torsvik, H., Cocks, L.R.M., 2013. Gondwana from top to base in space and time. *Gondwana Research*, 24, 999–1030.

TuchoIke, B.E., Houtz, R.E. and Barrett, D.M., 1981. Continental crust beneath the Agulhas Plateau. Southwest Indian Ocean. *J. Geophys*. Res., 86; 3791-3806.

Tucker R.D., Roig, J.Y., Moine B., Delor C., Peters S.G. 2014. A geological synthesis of the Precambrian shield in Madagascar. *Journal of African Earth Science*, 94, 9-30.

Verrier, F. Leprêtre, A.., Evain, M., Schnurle, P., Watremez, L, Aslanian, D., De Clarens, P., Afonso, N., Afilhado, A. Leroy, d'Acremont, E,, Castilla, R., Moulin, M., 2017. Preliminary results from combined wide-angle and reflection seismic data in the Natal Valley, South Mozambique margin across the Almirante Leite volcanic ridge: MZ2 profile (MOZ3/5 cruise). EGU 2017 Poster.

Viola, G., Henderson, I.H.C., Bingen, B., Thomas, R.J., Smethurst, M.A., de Azavedo, S., 2008. Growth and collapse of a deeply eroded orogen: insights from structural and geochronological constraints on the PanAfrican evolution of NE Mozambique. *Tectonics*, 27, TC5009, doi:10.1029/2008TC002284.

Watkeys, M.K. 2002. Development of the Lebombo Rifted Volcanic Margin of Southeast Africa. Geological Society of America, Special Papers, 362, 27–46.

Watkeys, M.K. and Sokoutis, D., 1998. Transtension in southeastern Africa associated with Gondwana break-up. In: R.E. Holdsworth, R.A. Strachan and J.F. Dewey (Editors), Continental transpressional and transtensional tectonics. *Geological Society, London, Special Publications*, pp. 203-214.

Wellman, P. and McDougall, I., 1974. Cainozoic igneous activity in eastern Australia. *Tectonophysics*, 23, 49-65.

Wellman, P., 1983. Hotspot volcanism in Australia and New Zealand: Cainozoic and Mid-Mesozoic. *Tectonophysics*, 96, 225 -243

Wessel, P., Smith, H.F., 1998. New, improved version of generic mapping tools released. *Eos*, 79, 47.

Windley, B.F., Razafiniparany, A., Razakamanana, T., Ackermand, D., 1994. Tectonic framework of the Precambrian of Madagascar and its Gondwana connections: a review and reappraisal. *Geol. Runds*., 83, 642–659.

Zaffarana, C.B., López de luchi, M.G., Somoza, R., Mercader, R., Giacosa, R., Martino, R.D., 2010. Anisotropy of magnetic susceptibility study in two classical localities of the Gastre Fault System, central Patagonia. *Journal of South American Earth Sciences*, 30, 151-166.

Figure Caption

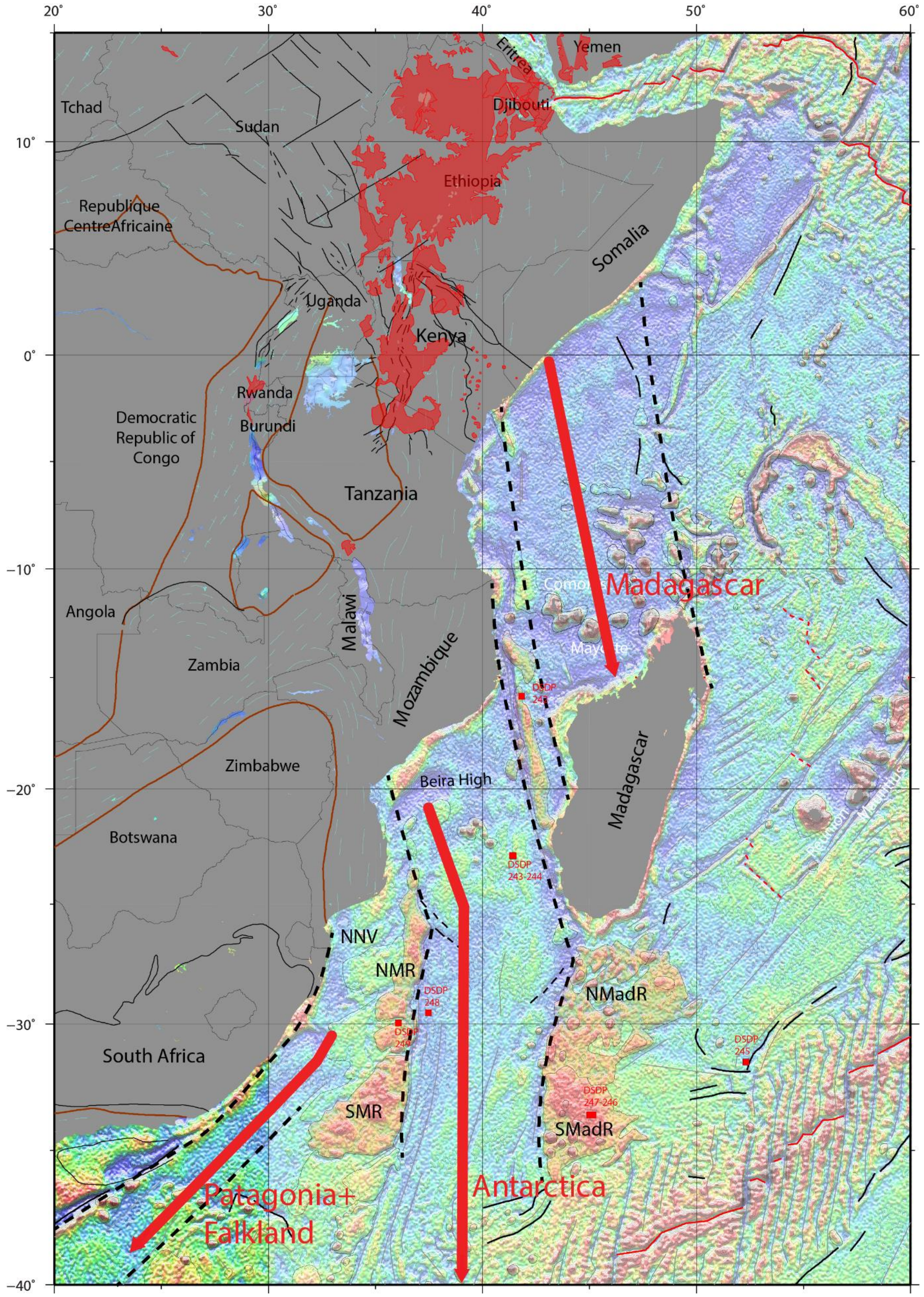


Figure 1: Gravity map of Mozambique Channel, showing the complexity and the segmentation of the East African margin. The upper and middle arrows correspond to the movement of

Madagascar and Antarctica tectonic plates respectively, and the westernmost arrow 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= East African Rift Volcanism . Mecator projection figure 1-3.

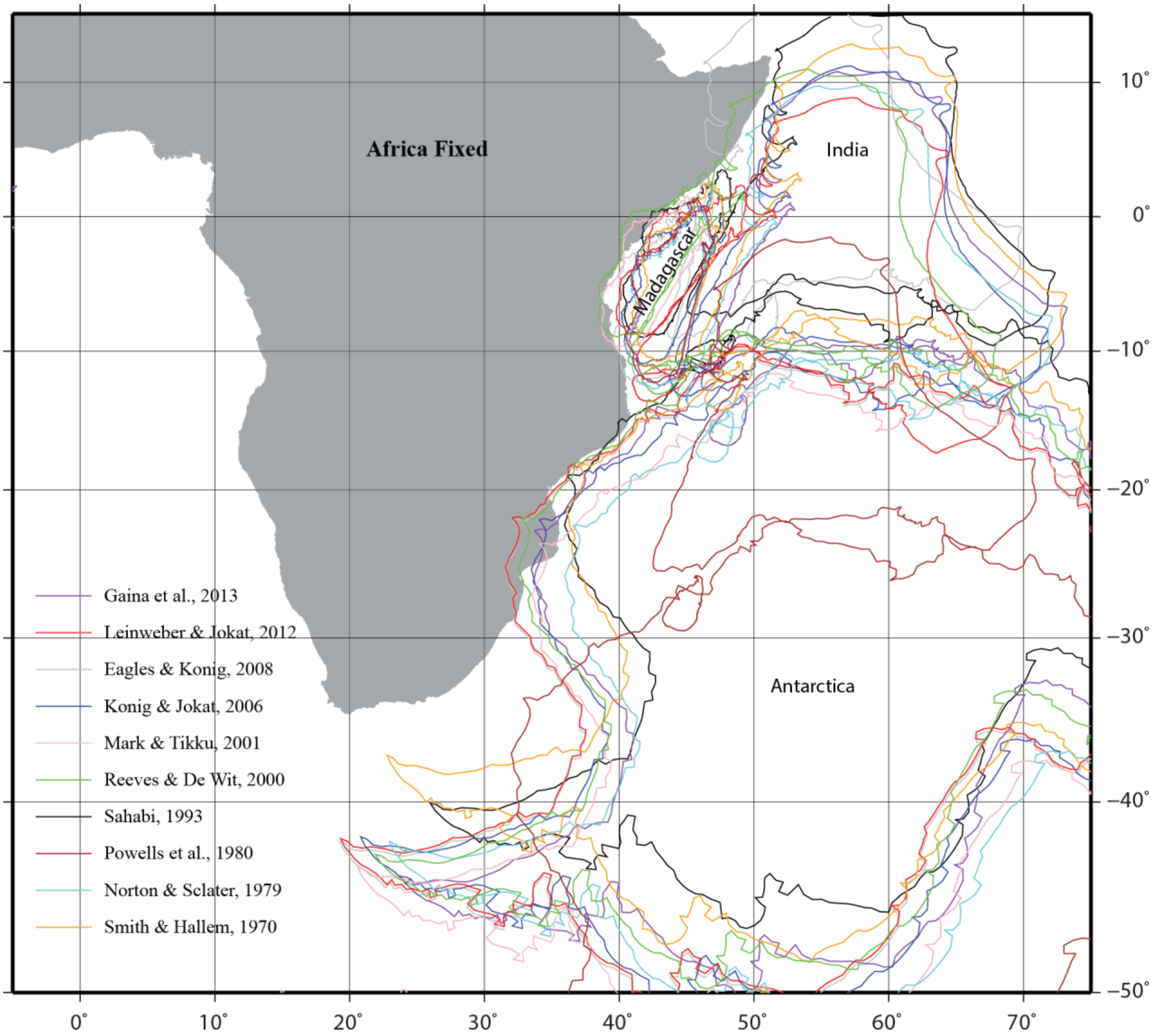


Figure 2: Selected kinematic reconstructions models of Gondwana's initial fit with respect to Africa, highlighting the large variations within the initial proposed fits. Note the multiple gaps and overlaps. These models are not consistent with the existing and new data (see text for further discussion).

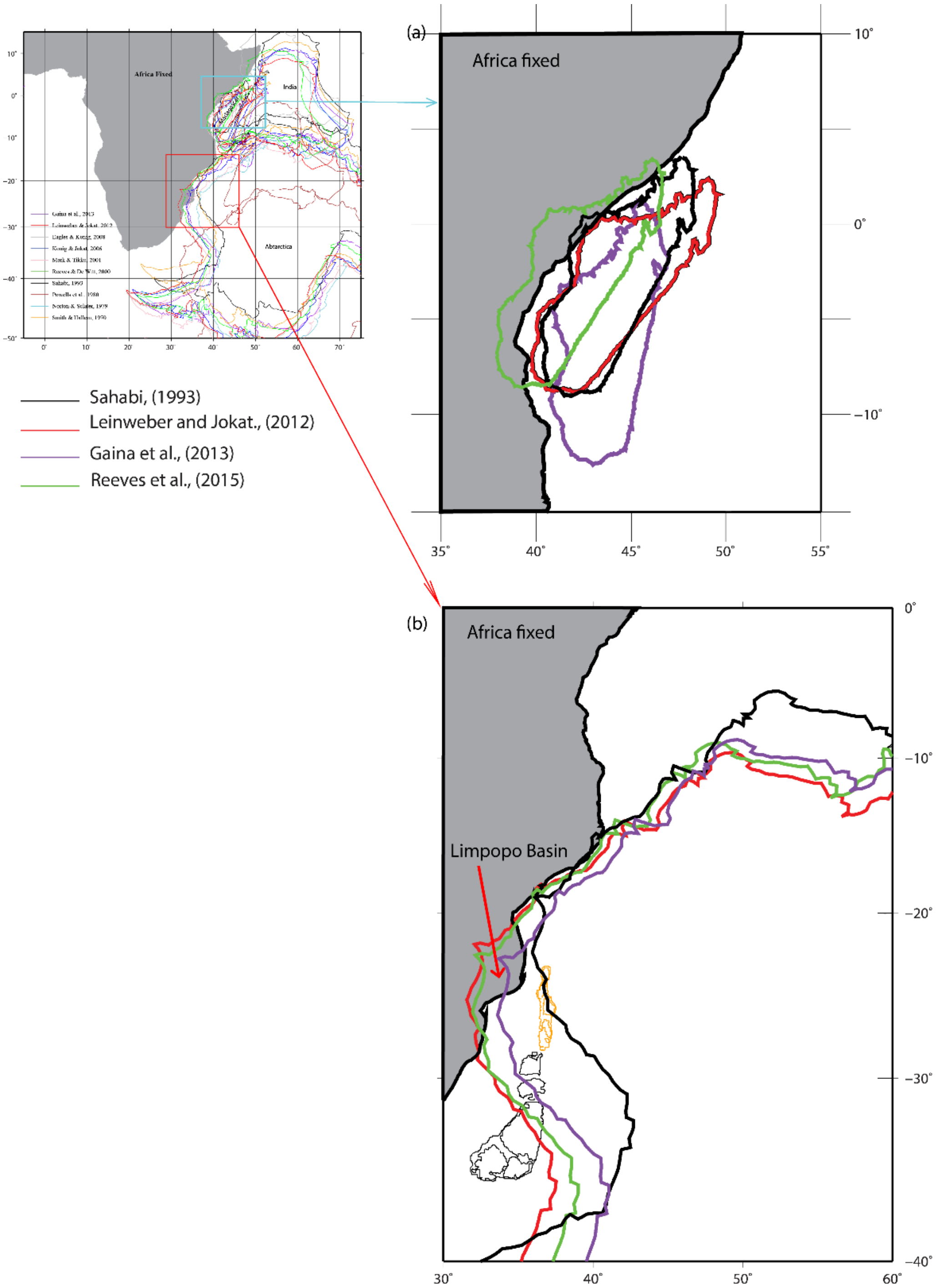


Figure 3: Zooms on figure 2 comparing the reconstruction models of Sahabi, (1993), Leinweber and Jokat, (2012), Gaina *et al.*, (2013), Reeves *et al.*, (2015) at the same scale. Notice the large differences in the placement of the plates in terms of latitude and angle. With regard to the fit between Africa and Antarctica, notice the overlap of Antarctica across the Limpopo basin in Reeves *et al.* (2015), Gaina *et al.* (2013) and Leinweber and Jokat, (2012). The North Mozambique Ridge (Yellow wedge line) was discovered during recent expedition in the Mozambique Basin of MOZ3-5 to consist mainly of sediments across thinned continental crust (Lepretre *et al.*, 2017). The Southern Mozambique Ridge (Black wedge line) maybe composed of volcanics emplaced at a triple junction.

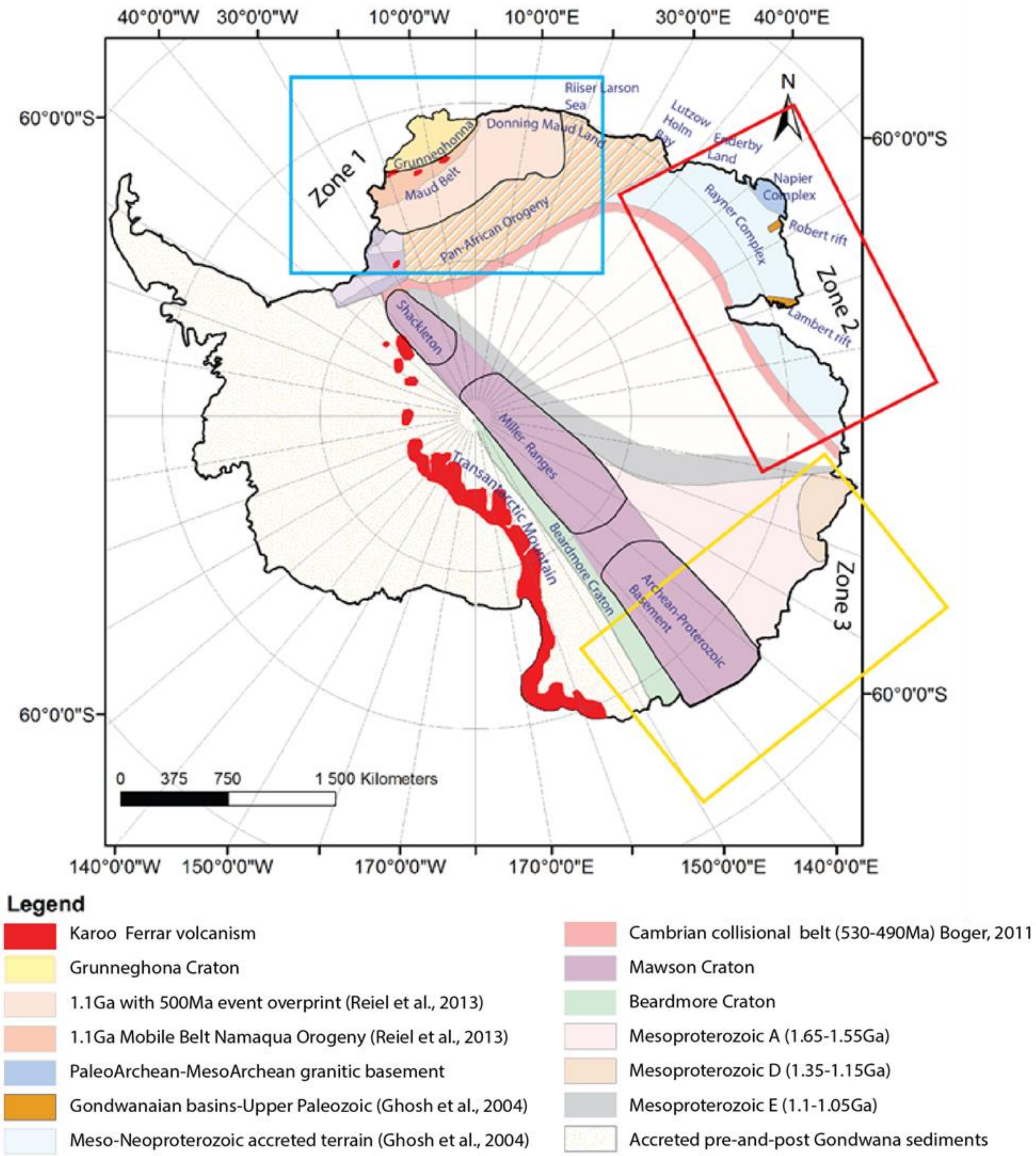
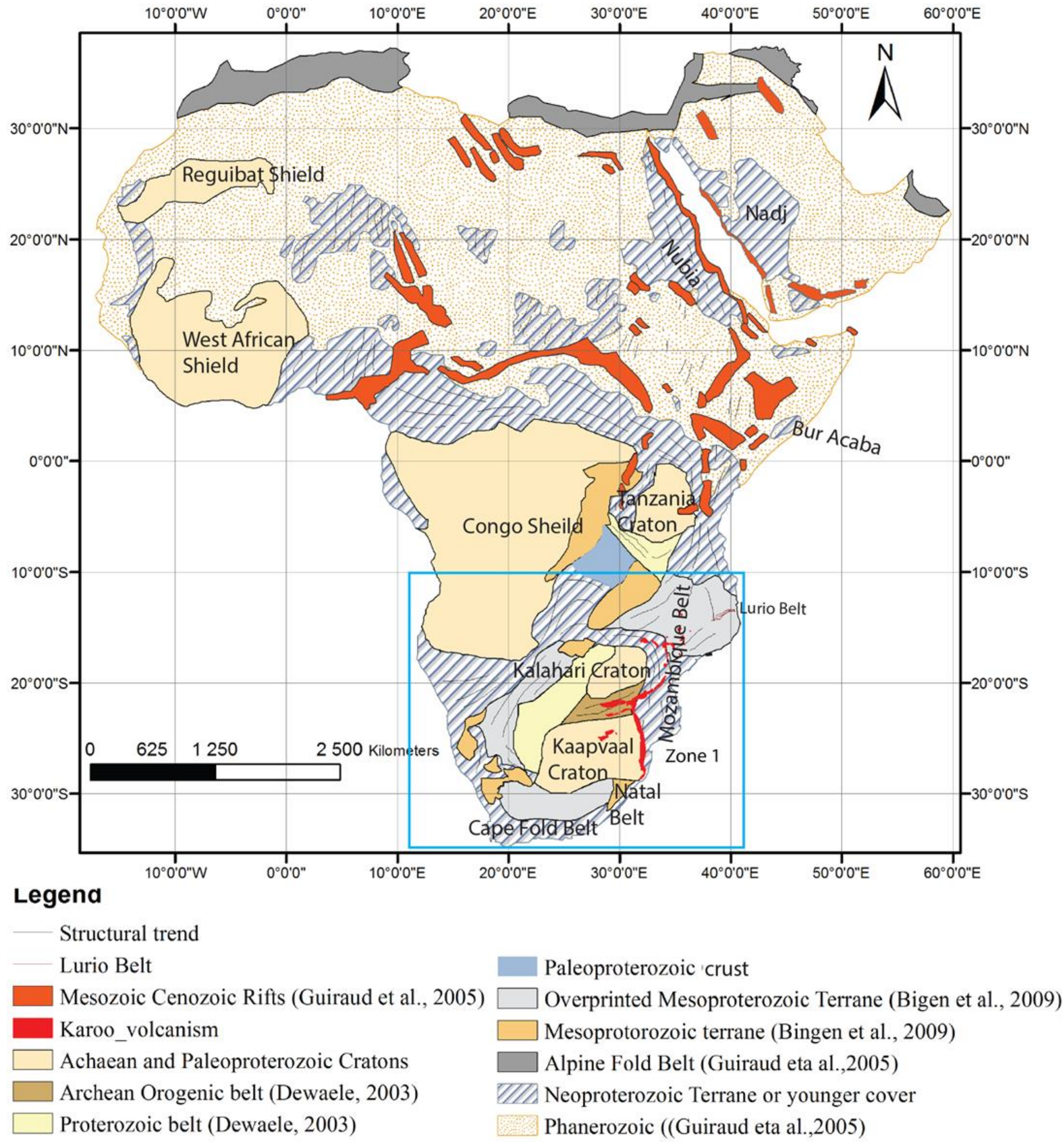


Figure 4: Basement geology of Antarctica compiled from (Rediel *et al.*, 2013: Boger, 2011: Ghosh *et al.*, 2004: Kelly *et al.*, 2002 – see Plate 1 supplementary material). Base on geochronological and similar orogenic history, Zone 1 (Blue rectangle) is linked to the Kaapval craton of Southern Africa, Zone 2 (Red rectangle) is linked to the rocks of Eastern Ghats of India, and Zone 3 (Yellow rectangle) is linked to the Australian plate. The traces of the Beardmore, Mawson, Mesoproterozoic (A, D, and E), and the location of the accreted pre-and-post Gondwana sediments in Antarctica and Australia are after Boger (2011). World Geodectic System 1984 figure 4-10.

References



10°0'0"W
0°0'0"
10°0'0"E
20°0'0"E
30°0'0"E
40°0'0"E
50°0'0"E
60°0'0"E
30°0'0"N
20°0'0"N
10°0'0"N
0°0'0"
10°0'0"S
20°0'0"S
30°0'0"S
N
Reguibat Shield
West African Shield
Nadj
Nubia
Bur Acaba
Congo Sheild
Tanzania Craton
Lurio Belt
Mozambique Belt
Kalahari Craton
Kaapvaal Craton
Zone 1
Natal Belt
Cape Fold Belt
0 625 1 250 2 500 Kilometers
Legend
Structural trend
Lurio Belt
Mesozoic Cenozoic Rifts (Guiraud et al., 2005)
Karoo_volcanism
Achaean and Paleoproterozoic Cratons
Archean Orogenic belt (Dewaele, 2003)
Proterozoic belt (Dewaele, 2003)
Paleoproterozoic crust
Overprinted Mesoproterozoic Terrane (Bigen et al., 2009)
Mesoprotorozoic terrane (Bingen et al., 2009)
Alpine Fold Belt (Guiraud eta al.,2005)
Neoproterozoic Terrane or younger cover
Phanerozoic ((Guiraud eta al.,2005)

(b)

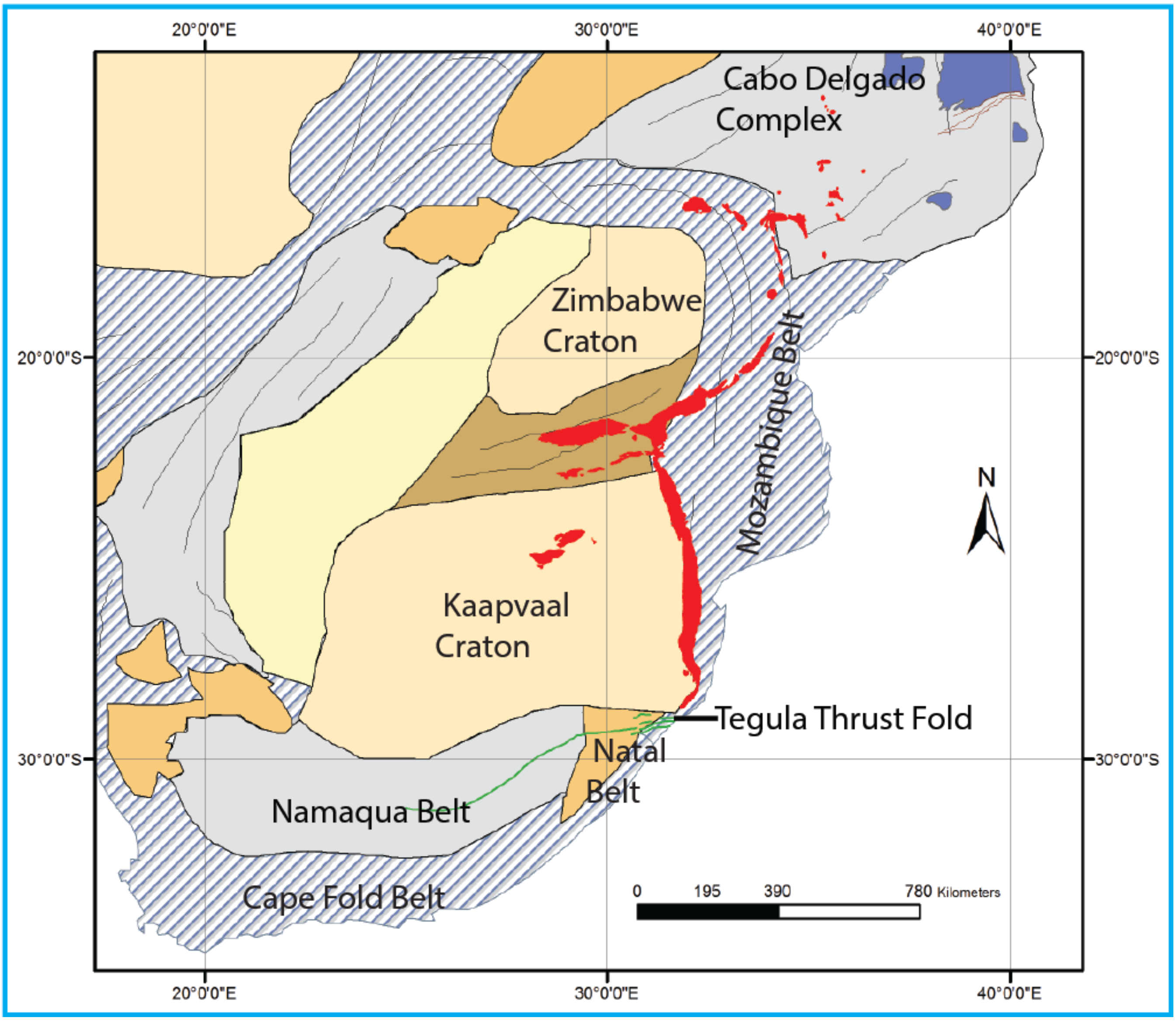


Figure 5: (a) Geological map of Africa compiled from (Foster *et al.*, 2015: Rekha *et al.*, 2014: Jacobs *et al.*, 2008: Guiraud *et al.*, 2005: Dewaele, 2003: Daly et al., 1989 – see Plate 2, supplementary material). The zone 1 (blue rectangle), marks a domain of shared geological similarities with Antarctica. (b) Zoom on figure 5a showing the domain of shared geological history with the Antarctica plate. The Kaapvaal Craton bear strong geochemical signatures similar to Grunnehogna cratons, most likely forming a single craton. The Namaqua-Natal belt was established during the Namaquan Orogeny, and is regarded as an extension of the Mesoproterozoic Maud Belt in Antarctica.

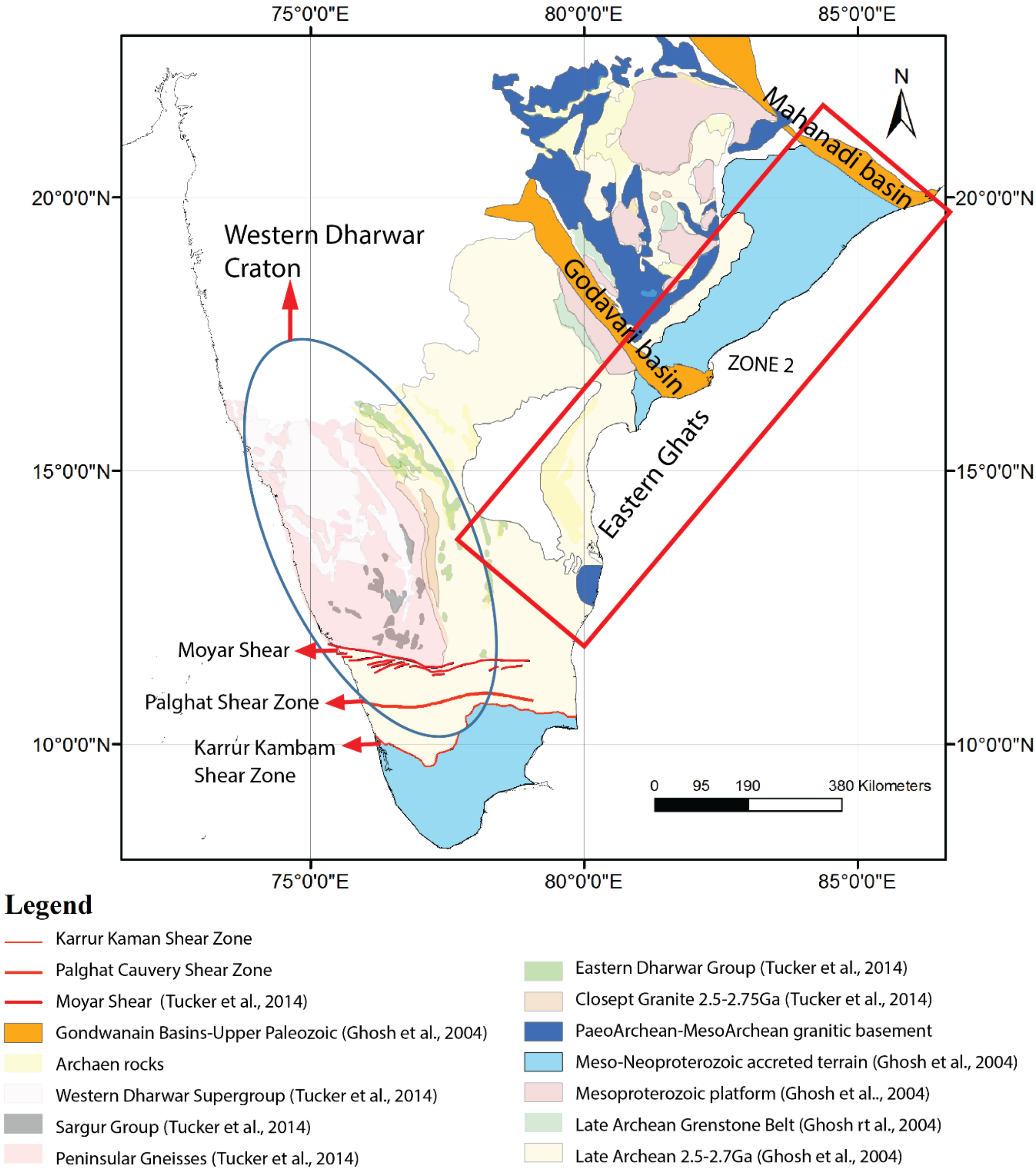


Figure 6: Geology of India basement compiled from (Tucker *et al.*, 2014; Rajaprian *et al.*, 2014; Dasgupta *et al.*, 2013; Ghosh et al., 2004; and www.portal.gsi.gov.in/portal 11/07/2016 – see Plate 3 supplementary material). The marked area zone 2 indicates area of sheared geological similarities with Antarctica. Rocks of the Ghats share similar geochronological properties with rocks of Enderby Land in East Antarctica. The Dharwar craton of India share similar geochemical and geochronological properties with the Archean rocks of Madagascar.

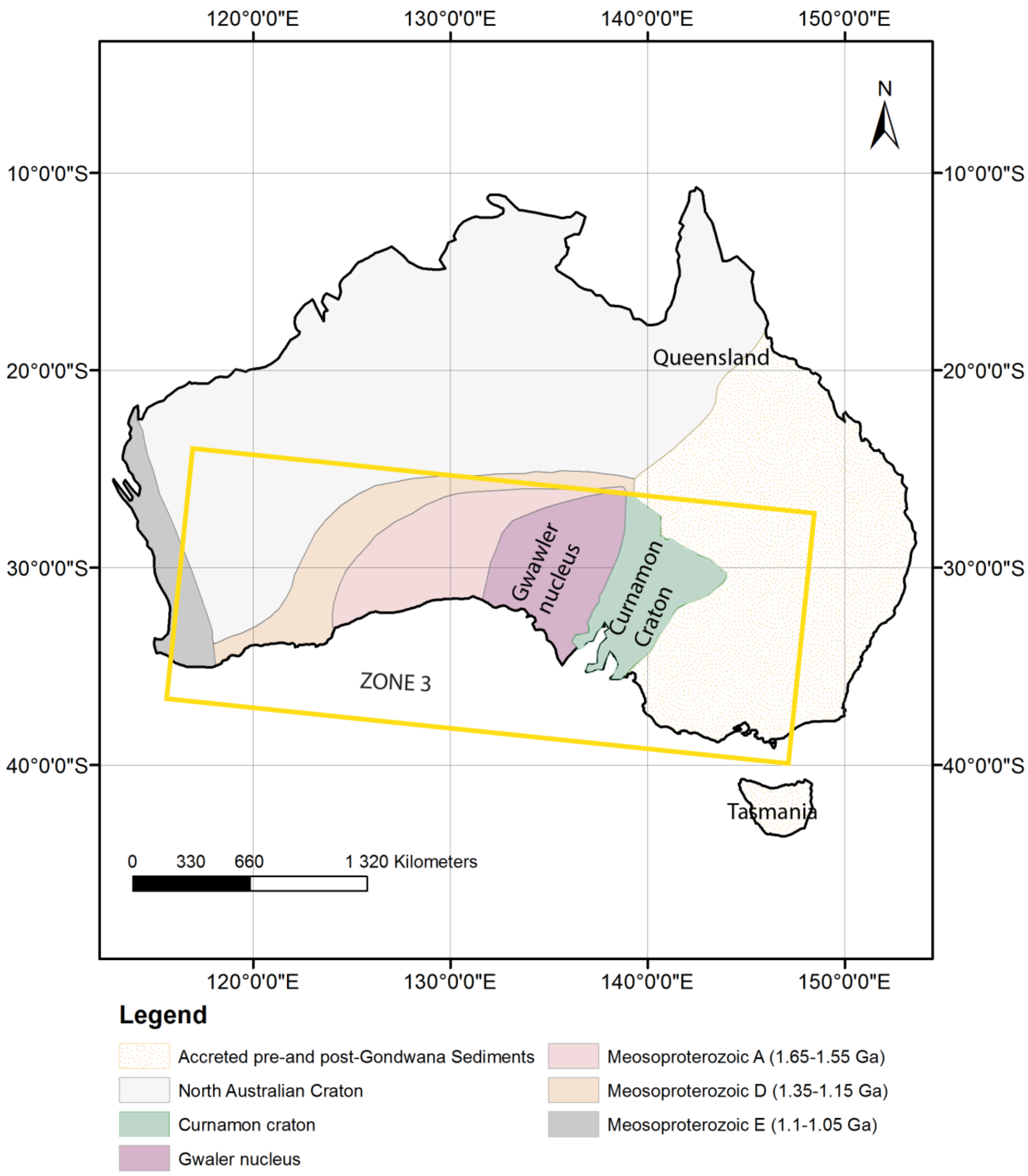
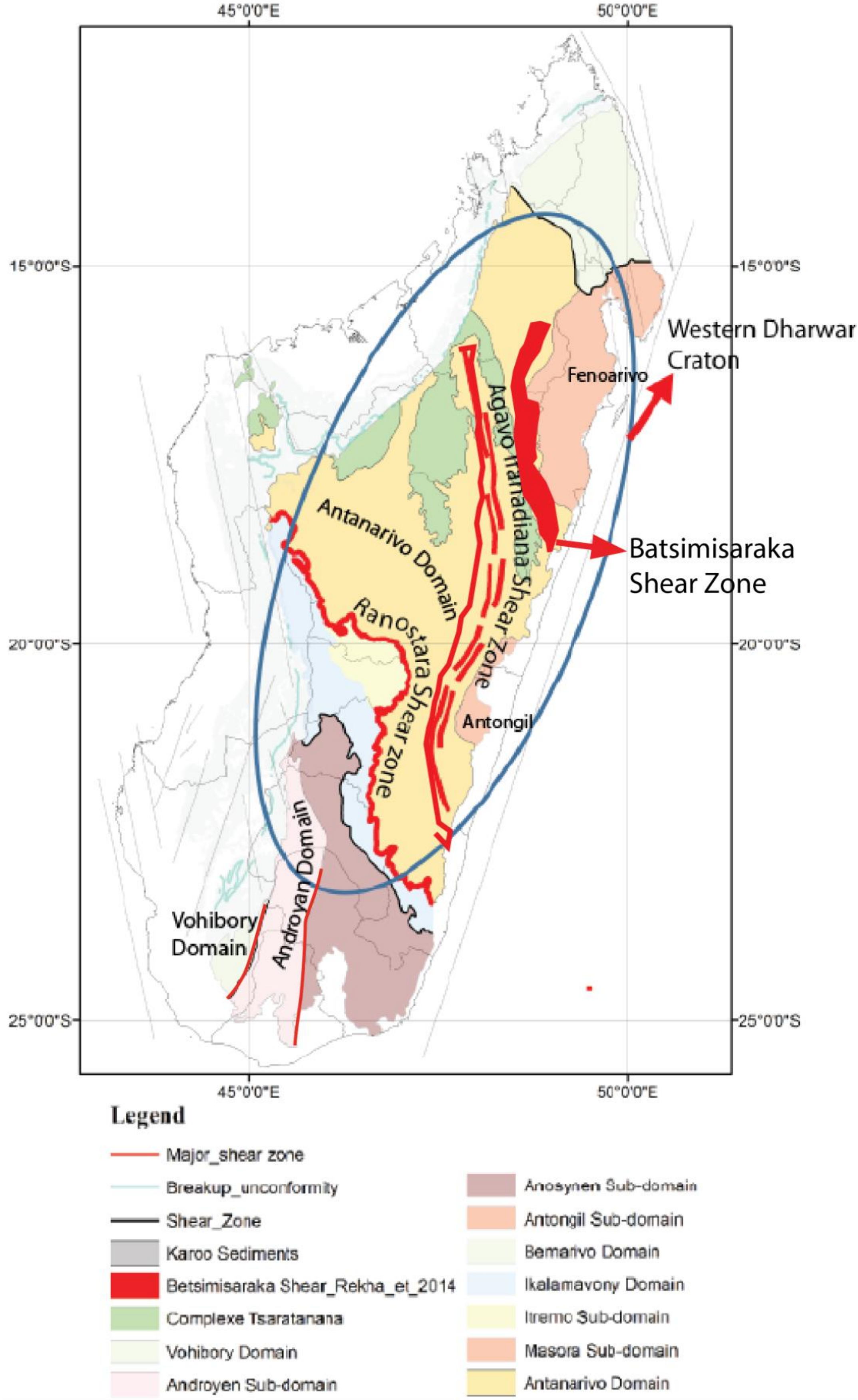


Figure 7: Basement geology of the Australian modified (after Borg and DePaolo, 1991 and Boger, 2011 - – see Plate 4 supplementary material). Zone 3 indicates area of similar geological signatures with Antarctica. The Mawson and Beadmore blockss of Antarctica continue into the Gawler and Curnamon blocks in Antarctica respectively with similar geochronologically characteristics (Boger, 2011).



45°0'0"E
50°0'0"E
15°0'0"S
20°0'0"S
25°0'0"S
Western Dharwar Craton
Fenoarivo
Batsimisaraka Shear Zone
Antananarivo Domain
Agavo Ifanadiana Shear Zone
Ranostara Shear zone
Antongil
Androyan Domain
Vohibory Domain
Legend
Major_shear zone
Breakup_unconformity
Shear_Zone
Karoo Sediments
Betsimisaraka Shear_Rekha_et_2014
Complexe Tsaratanana
Vohibory Domain
Androyen Sub-domain
Anosynen Sub-domain
Antongil Sub-domain
Bemarivo Domain
Ikalamavony Domain
Itremo Sub-domain
Masora Sub-domain
Antanarivo Domain

Figure 8: Geology of Madagascar compiled from (Tucker *et al.*, 2014: Rekha *et al.*, 2014: Rasoamalala *et al.*, 2014, de Wit et al., 2001; Nesen *et al.*, 1988: Courrier and Lafont, 1987: Besairie and Collignon, 1972 – see Plate 5 supplementary material). The Archean rocks of Madagascar shares similar geochemical and geochronological properties with the Dharwar craton in India. The Batsimisaraka shear zone in Rkha *et al.*, 2014, is argued by Tucker *et al.*, 2014 not to be evident.

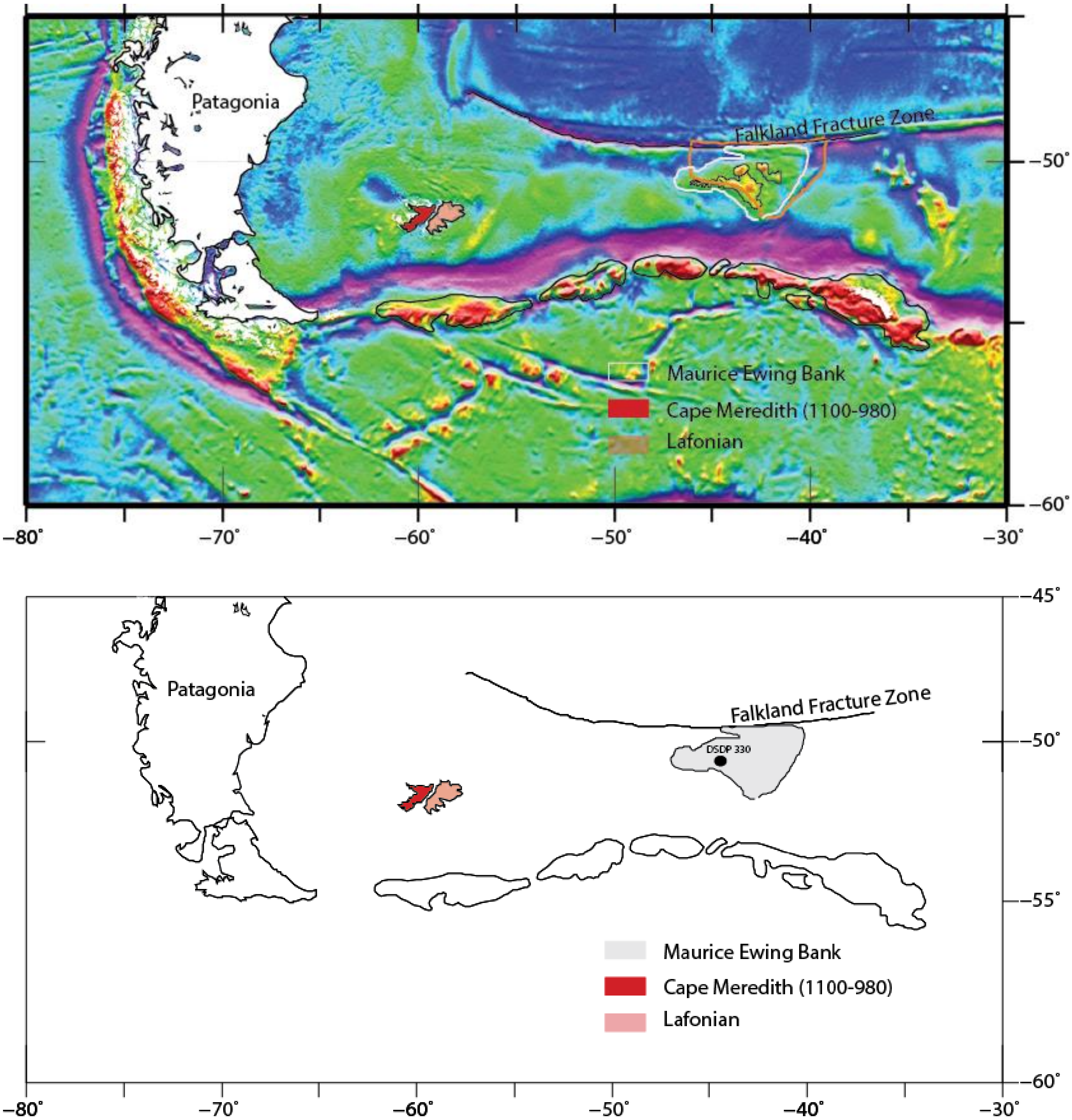


Figure. 9: Geological map of the Falkland Plateau compiled from (Lock, 1978; Martin *et al.*, 1982; Marshall, 1994; Curtis and Hyam, 1998). DSDP Hole 330 was bottomed in Precambrian rocks (554± 66Ma Lorenzo and Mutter, 1988) correlative with the PanAfrican ~650-500Ma Cape basement of Southern Africa.

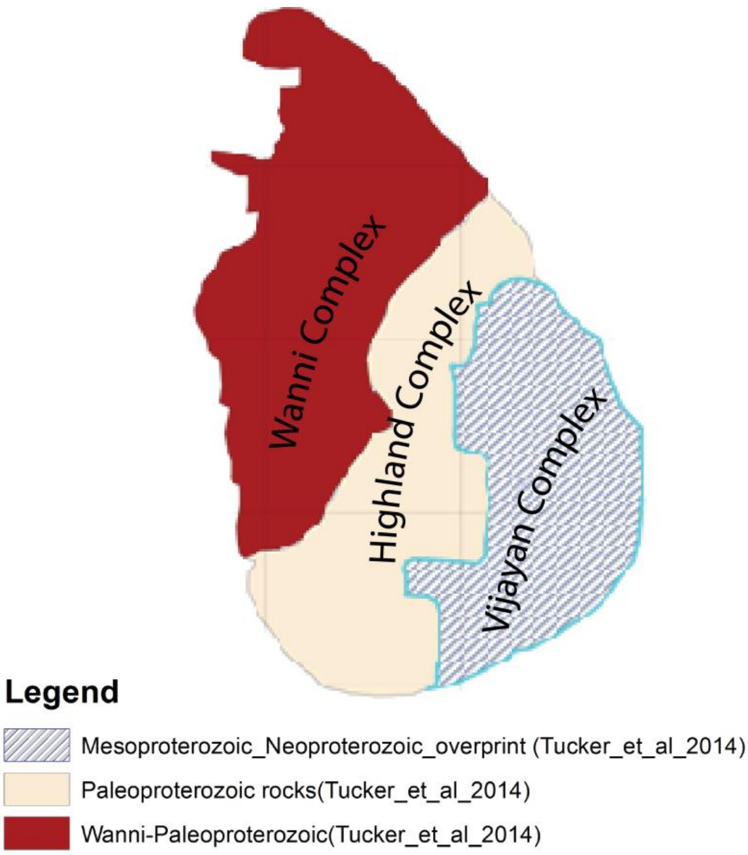


Figure 10: Basement geology map of Sri Lanka (modified after Koner *et al.*, 2003; Bingen *et al.*, 2009; Kelly *et al.*, 2002; and Tucker *et al.*, 2014– see Plate 6 supplementary material).

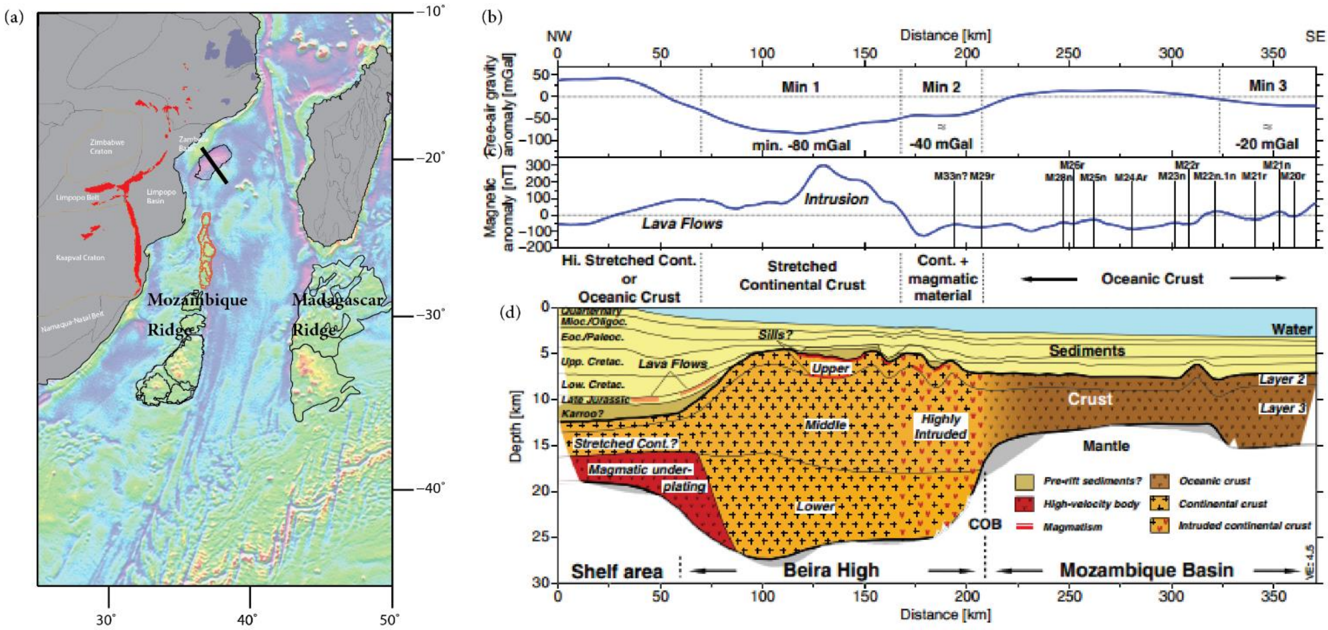
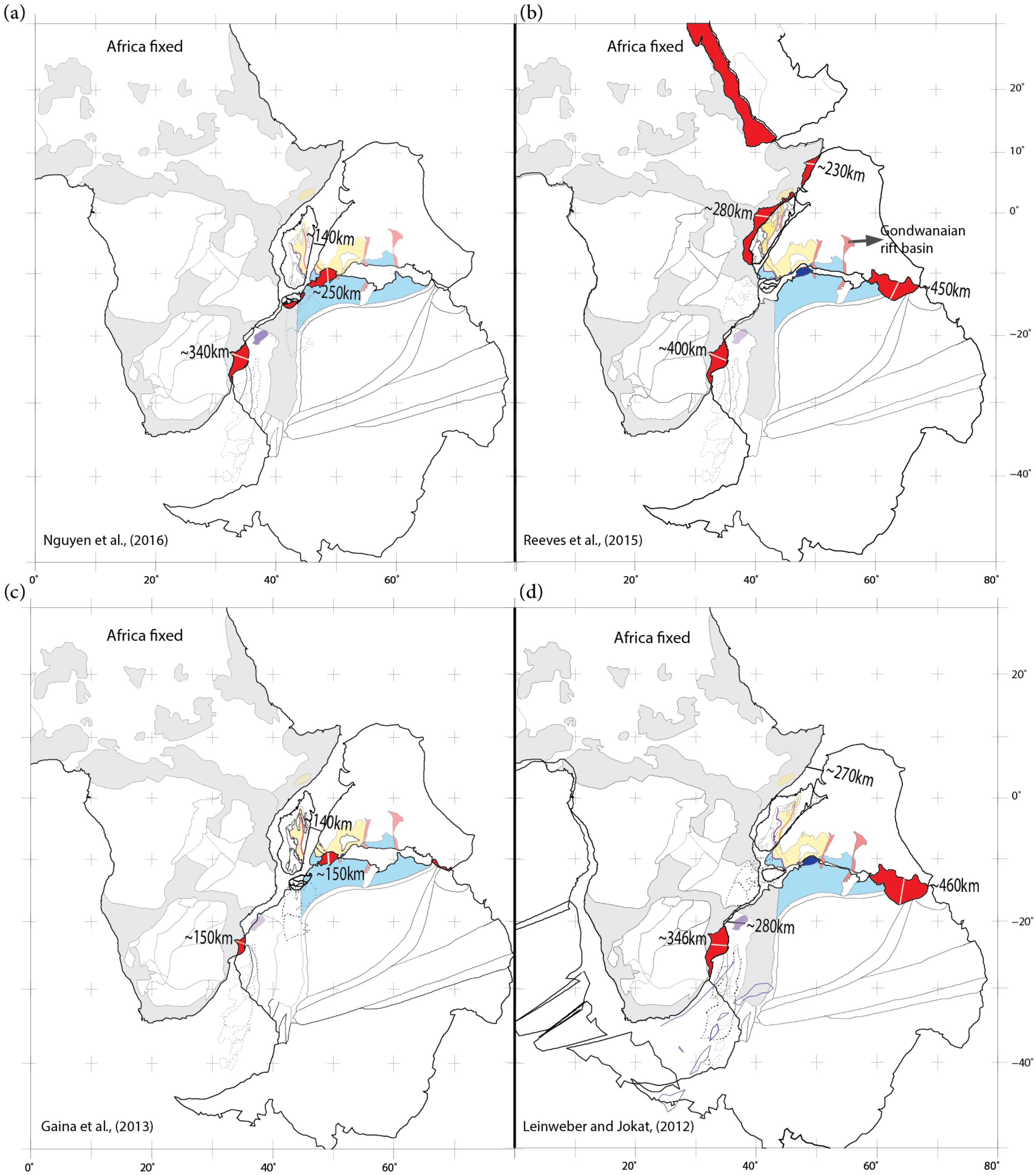
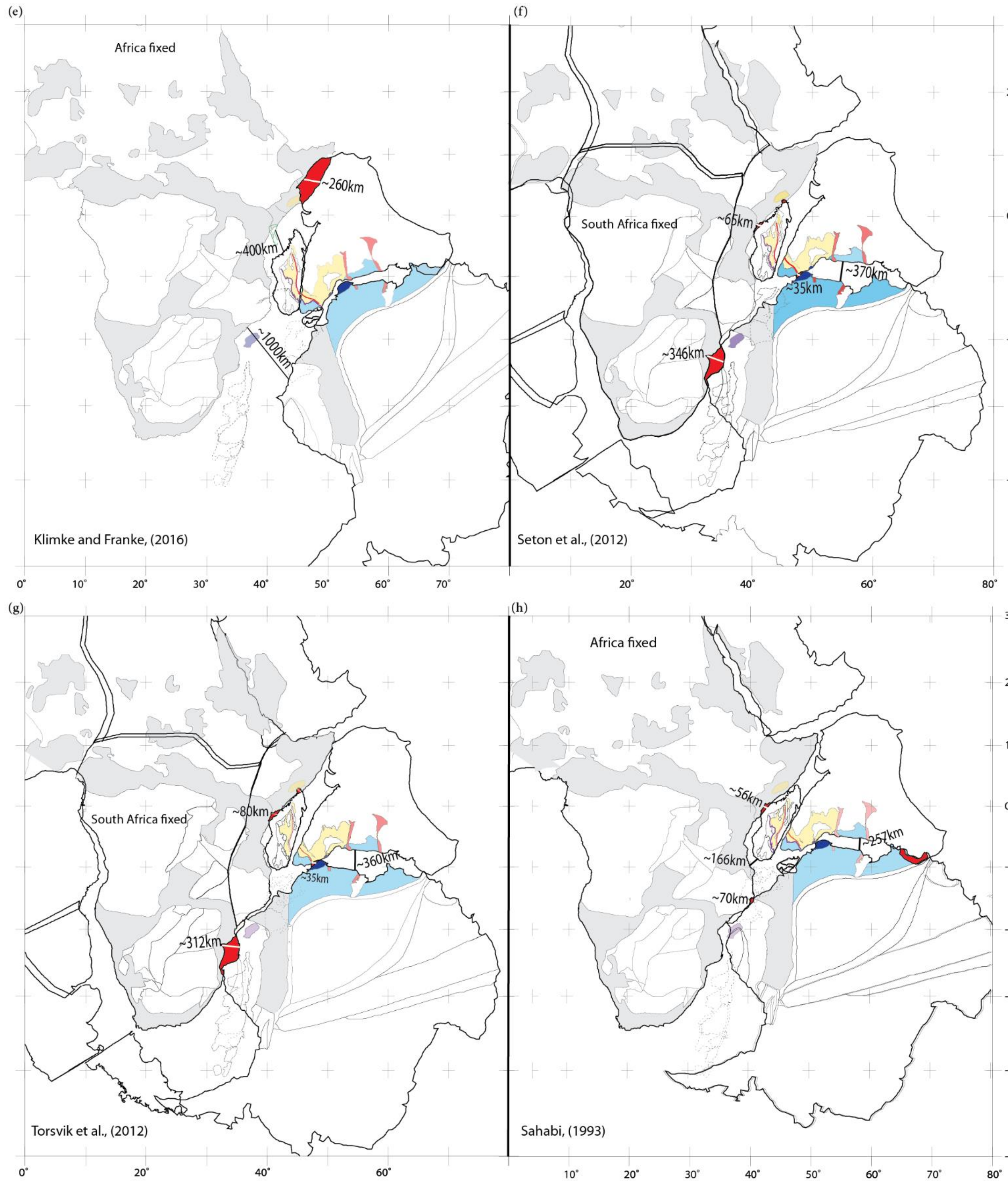


Figure 11: (a) Sandwell *et al.*, (2014) free-air satellite-derived gravity anomaly of the Mozambique Channel. The black line on the Beira High shows the location of the seismic refraction profile 2014001014 of Mueller et al. (2016). The North Mozambique Ridge (In red) during recent expedition in the Mozambique Basin of MOZ3-5 was found to consist mainly of sediments muscle on a thinned continental crust (Lepretre *et al.*, 2017). The Southern Mozambique Ridge (In black) maybe composed of volcanics (Gohl et al., 2011) probably emplaced at a triple junction. Outline of Beira High generated from Total seismic reflector data in the Zambezi Basin. (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) Mueller *et al.*, (2016) interpretation of wide-angle seismic profile 2014001014 seismic across the Beira High and the Zambezi depression. They interpreted the Beira High to be of continental origin, and that the Zambezi depression consists of intruded stretched continental crust. Mercator projection figure 11-23.


(a)
Africa fixed
~140km
~250km
~340km
Nguyen et al., (2016)
(b)
Africa fixed
~230km
~280km
Gondwanaian rift basin
~450km
~400km
Reeves et al., (2015)
20°
10°
0°
−20°
−40°
0°
20°
40°
60°
80°
(c)
Africa fixed
~140km
~150km
~150km
Gaina et al., (2013)
(d)
Africa fixed
~270km
~460km
~346km
~280km
Leinweber and Jokat, (2012)
20°
0°
−20°
−40°
0°
20°
40°
60°
20°
40°
60°
80°

Article submitted.



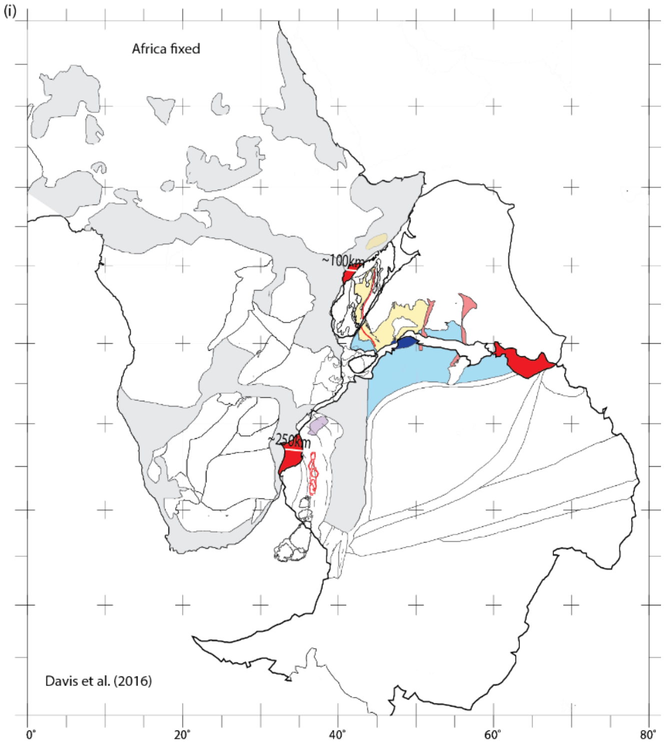


Figure.12 Comparing the kinematic models of Nguyen *et al.* (2016), Klimbe and Franke (2016), Davis et al. (2016), Reeves *et al.* (2015), Gaina *et al.* (2013), Leinweber and Jokat, (2012), Seton *et al.* (2012), Torsvik *et al.* (2012) and Sahabi (1993). The red, ash, blue, yellow and deep blue polygons represents overlap, Neoproterozoic terrain, Mesoproterozoic accreted terrain, Late Archean rocks, Paleo-Meso Archean rocks respectively. In Davis et al. (2016), Reeves *et al.* (2015) and Leinweber and Jokat (2012), the Agavo Ifanadiana shear zone (Madagascar) is aligned with the Moyar shear zone (West India). This results in large overlap between India and Antarctica. Gaina *et al.* (2013) and Sahabi (1993) on the other hand, fit the Batsimisaraka 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 a perfect alignment of Archean rocks of the Napier complex and the Ghat craton and a good alignment of the Gondwanan rifts basins. Klimbe and Franke (2016) prefer a more southward position of Madagascar leading to huge gap of about 1000km between Antarctic and Africa taken into consideration current information and observations we have gathered on the surrounding plates.

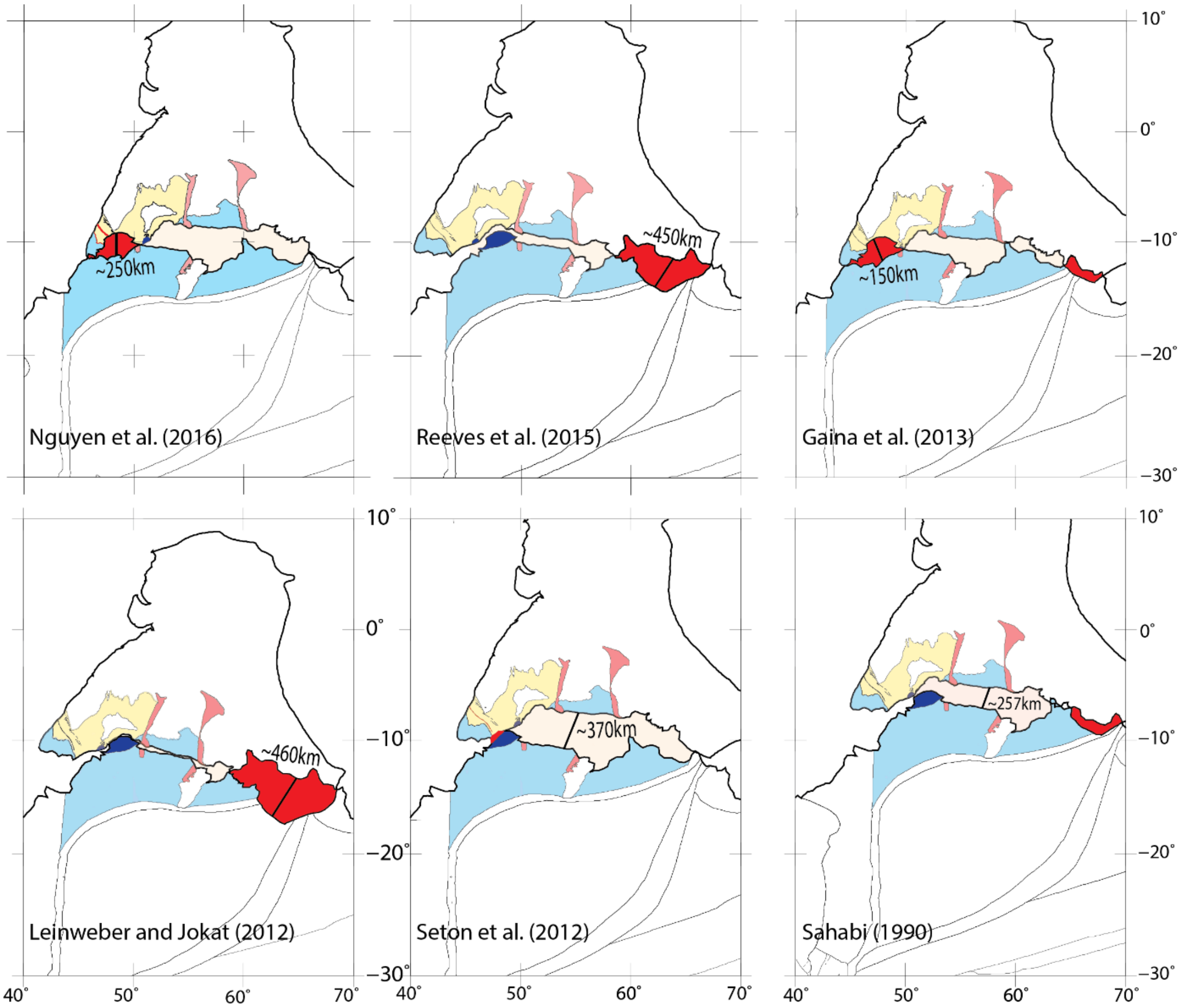


Figure 13: Comparism (zoom) of India and Antarctica with referencee to Africa for the models of Nguyen *et al.* (2016), Reeves *et al.* (2015), Gaina *et al.* (2013), Leinweber and Jokat (2012), Seton *et al.* (2012), and Sahabi (1993). The models of Nguyen *et al.* (2016), Gaina *et al.* (2013) and 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 results 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). The pink color represent gap, the rest of the legend is same as in figure 11.

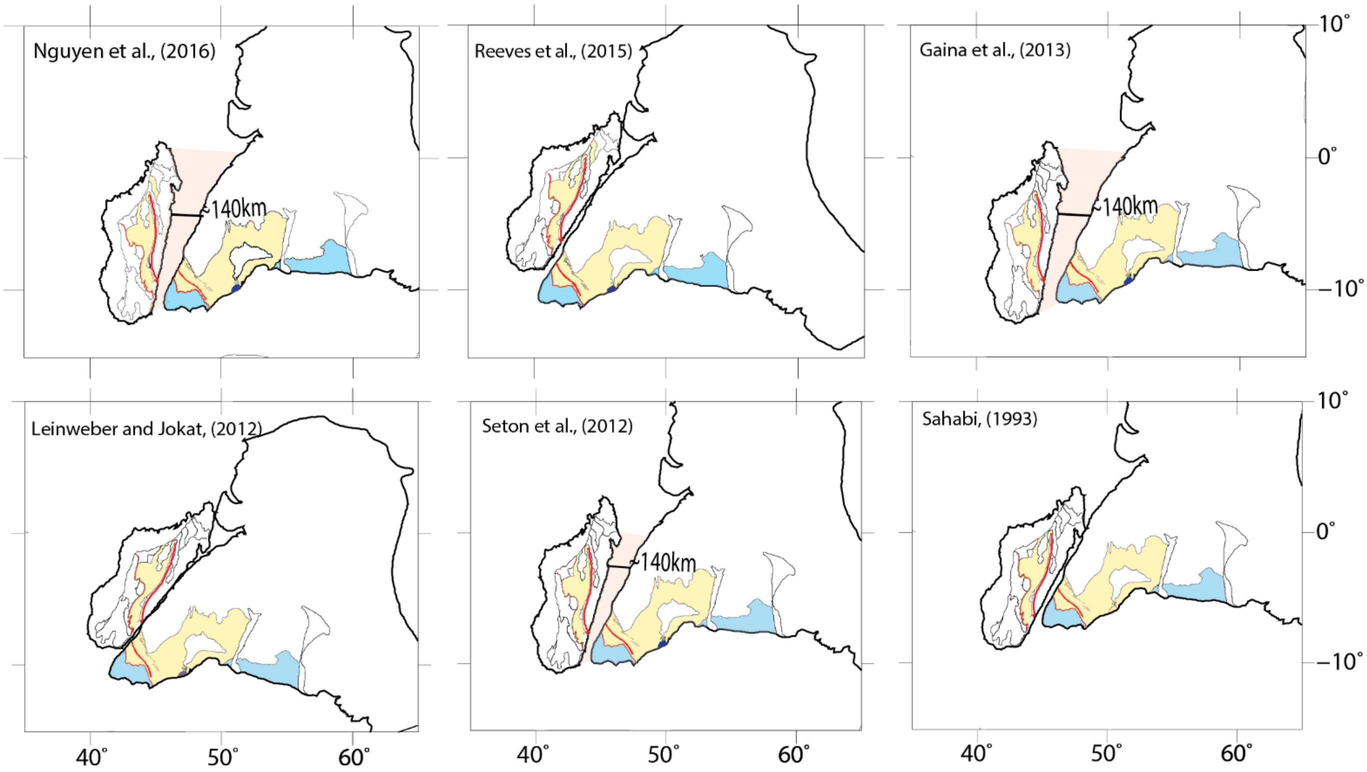


Figure 14: Kinematic reconstruction models Comparism of Madagascar and India with referencee to Africa in Nguyen et al., (2016), Reeves et al., (2015), Gaina et al., (2013) and Leinweber and Jokat, (2012) Seton et al., (2012), and Sahabi, (1993). In Reeves et al., (2015) and Leinweber and Jokat, (2012), 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 inaccurately fits Mesoproterozoic rocks to Archean rocks between the two plates. The pink color represent gap, the rest of the legend is same as in figure 11.

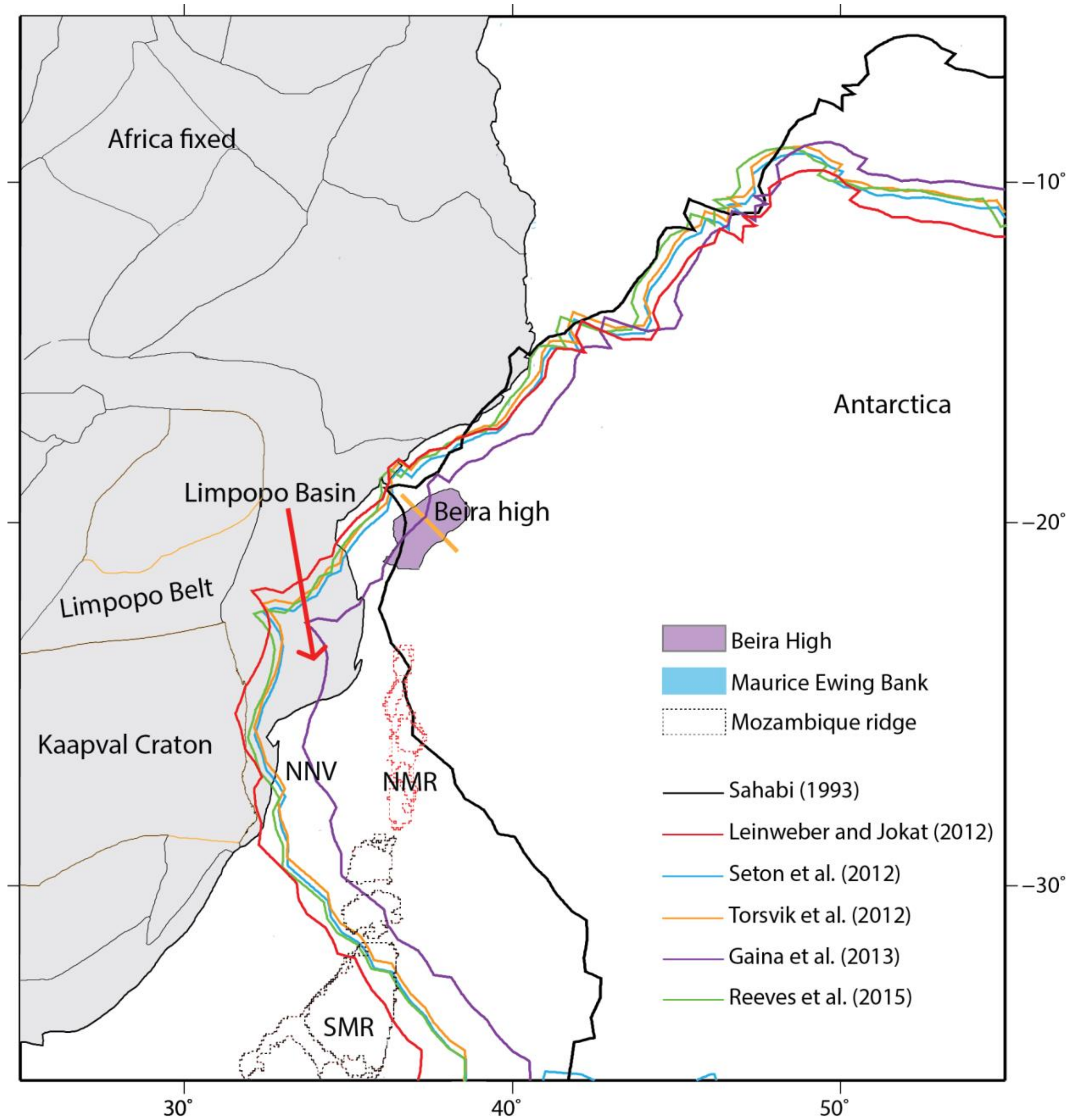


Figure 15: Comparing the fits between Antarctica with respect to Africa, and the consequence on the Beira High continental crust and the Limpopo basin. The yellow line crossing the Beira High continental block shows the location of the seismic refraction profile 2014001014 of the MOCOM-Cruise (See figure 11). Notice all the models except Sahabi, (1993) overlap on the Beira high, the North Natal Valley, a part or the total Limpopo Basin and the North Mozambique ridge. The North Mozambique Ridge (NMR, in red) consists mainly of sediments muscle on a thinned continental crust (Lepretre *et al.*, 2017). The Southern Mozambique Ridge (SMR, in black) maybe composed of volcanics (Gohl et al., 2011).

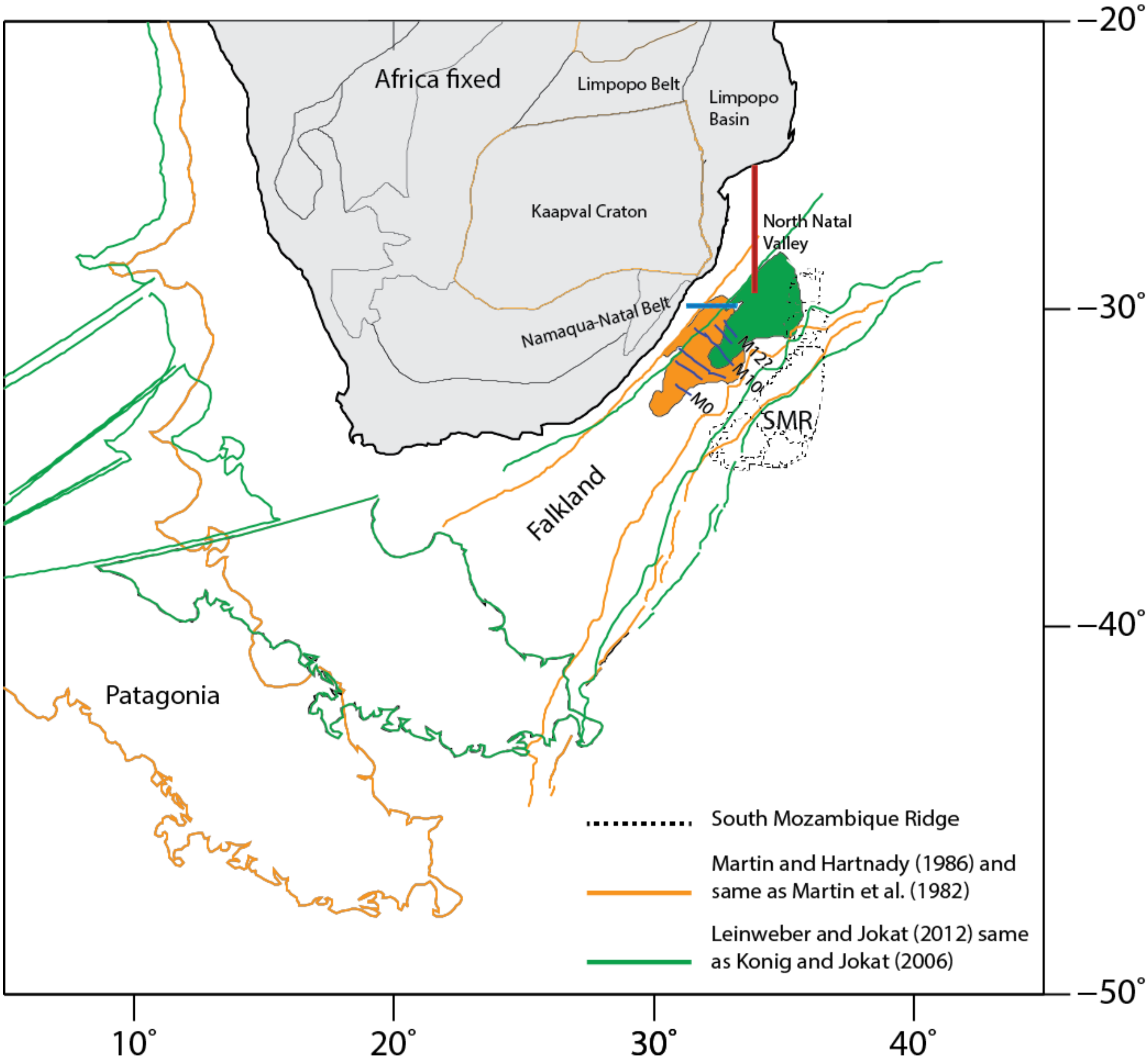


Figure 16: Comparing the proposed fit for the Falkland-Patagonia in the reconstruction of Martin and Hartnady (1986) and Martin *et al.* 1982, and the models Leinweber and Jokat (2012) and Konig and Jokat (2006) relative to African plate. Notice Leinweber and Jokat (2012) and Konig and Jokat (2006) (orange) significantly overlap the North Natal Valley, which is underlain by continental crust (Lepretre *et al.* (2017). Red line: refraction profile M7 Pamela Moz3-5 of Lepretre *et al.* (2017). Lepretre *et al.* (2017), showed that the oceanic crust in the Natal Valley commences just at the southern end of the profile; Blue line the limit of the South Tegula Ridge. The South Tegula Ridge previously considered by Martin et al., (1982) as the effective northern limit of the Maurice Ewing Bank beyond, beyond which it cannot be accommodated. SMR= South Mozambique Ridge.

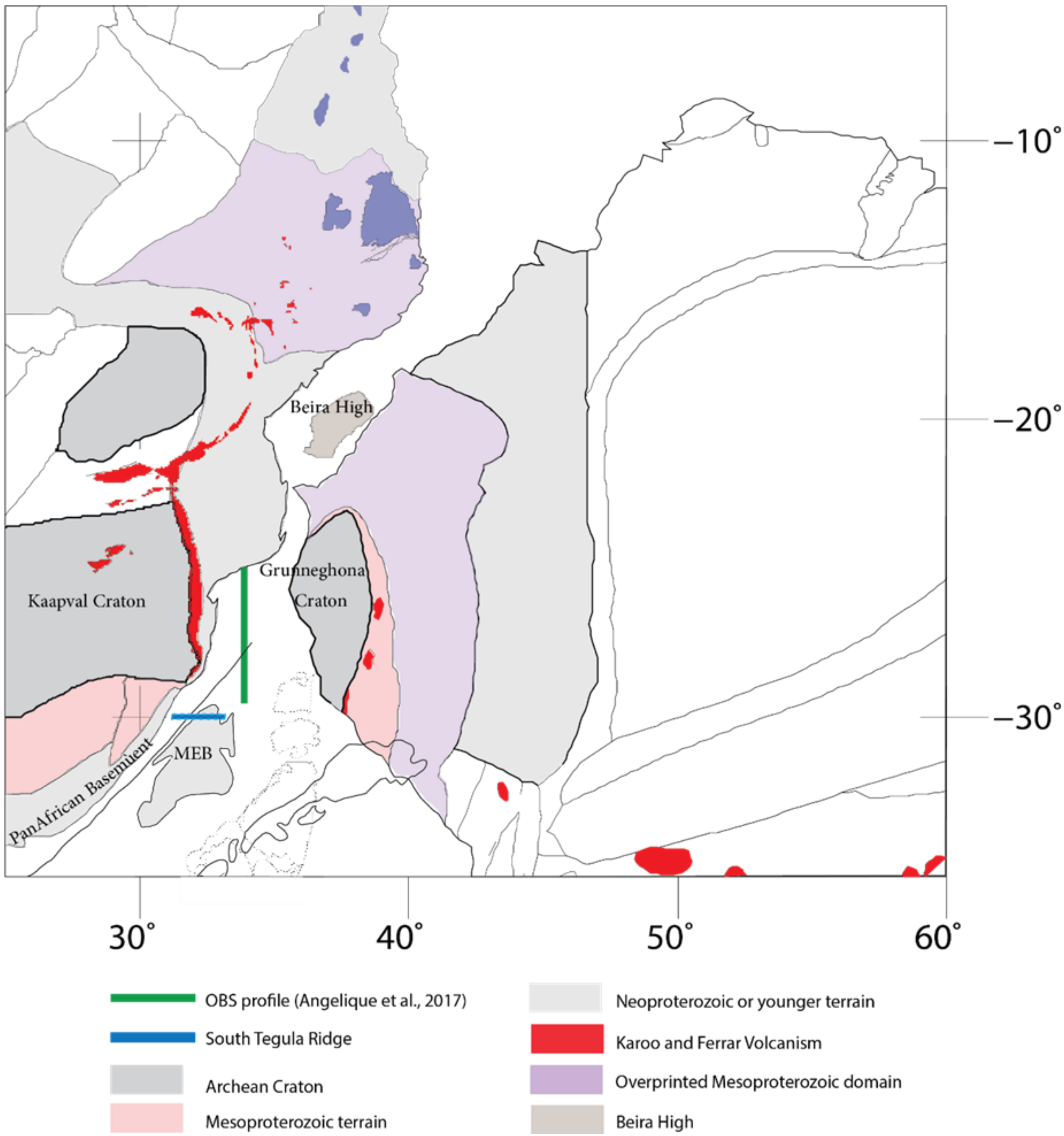


Figure 17: Map showing our reconstruction of Antarctica with respect to Africa. . Notice the Antarctica plate do not overlap the Beira High continental crust, and the extent of the Archean Kaapval and Grunneghona Craton. The two cratons bears strong geochemical signatures with each other. The reconstruction of the Falkland Plateau to Africa shows the similarities between the geology of the PanAfrican basement and the rocks of the Maurice Ewing Bank. Green line: refraction profile M7 Pamela Moz3-5 of Lepretre *et al.* (2017); Blue line the limit of the South Tegula Ridge.

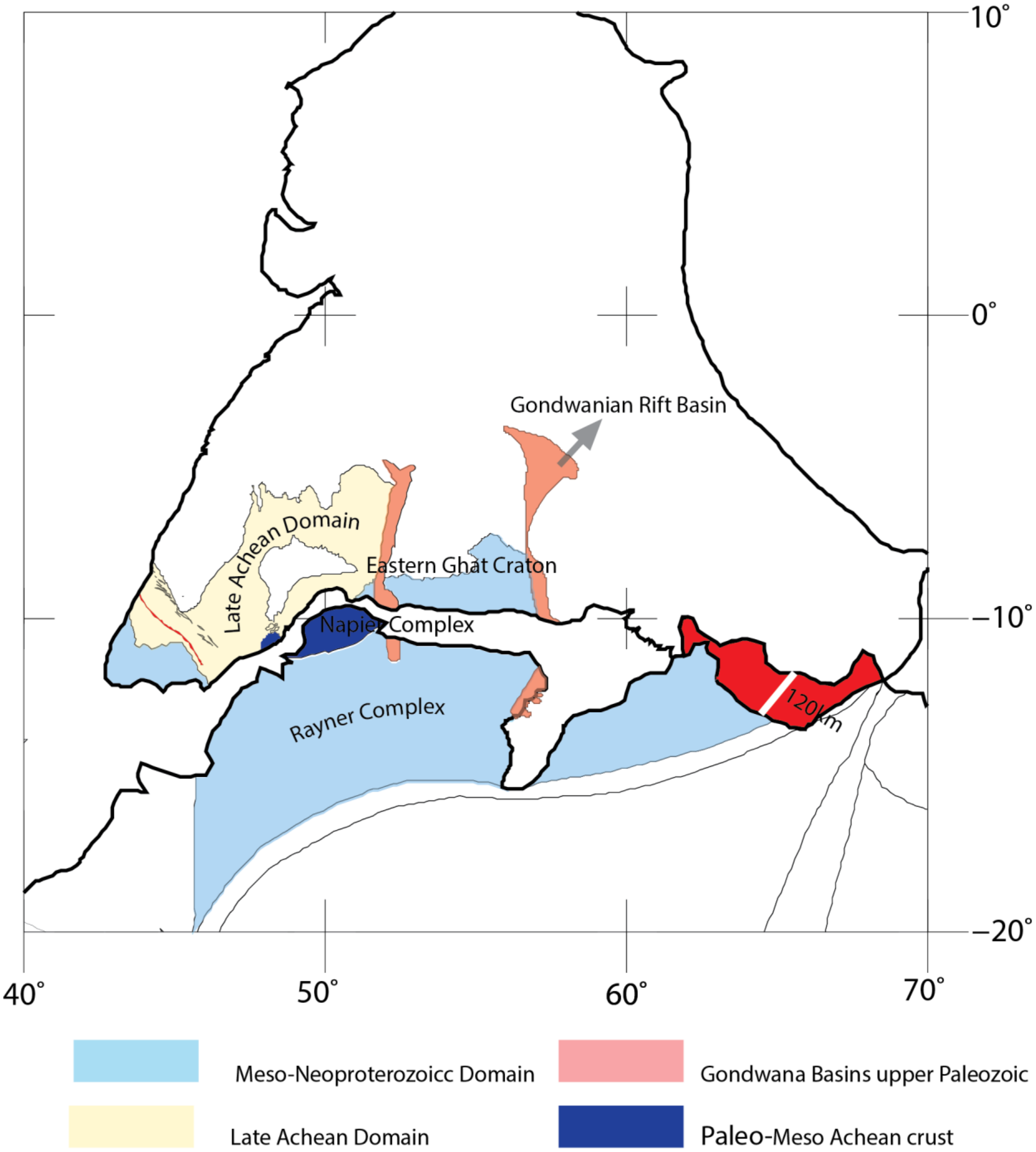


Figure 18: Map showing our reconstruction of India and Antarctica (with respect to Africa). The Archean rocks of the Napier complex in Antarctica and the Eastern Ghats craton share similarly geochemical characteristics. The Rayner Complex extends from Enderby Land (Antarctica) into the Mesoproterozoic 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.

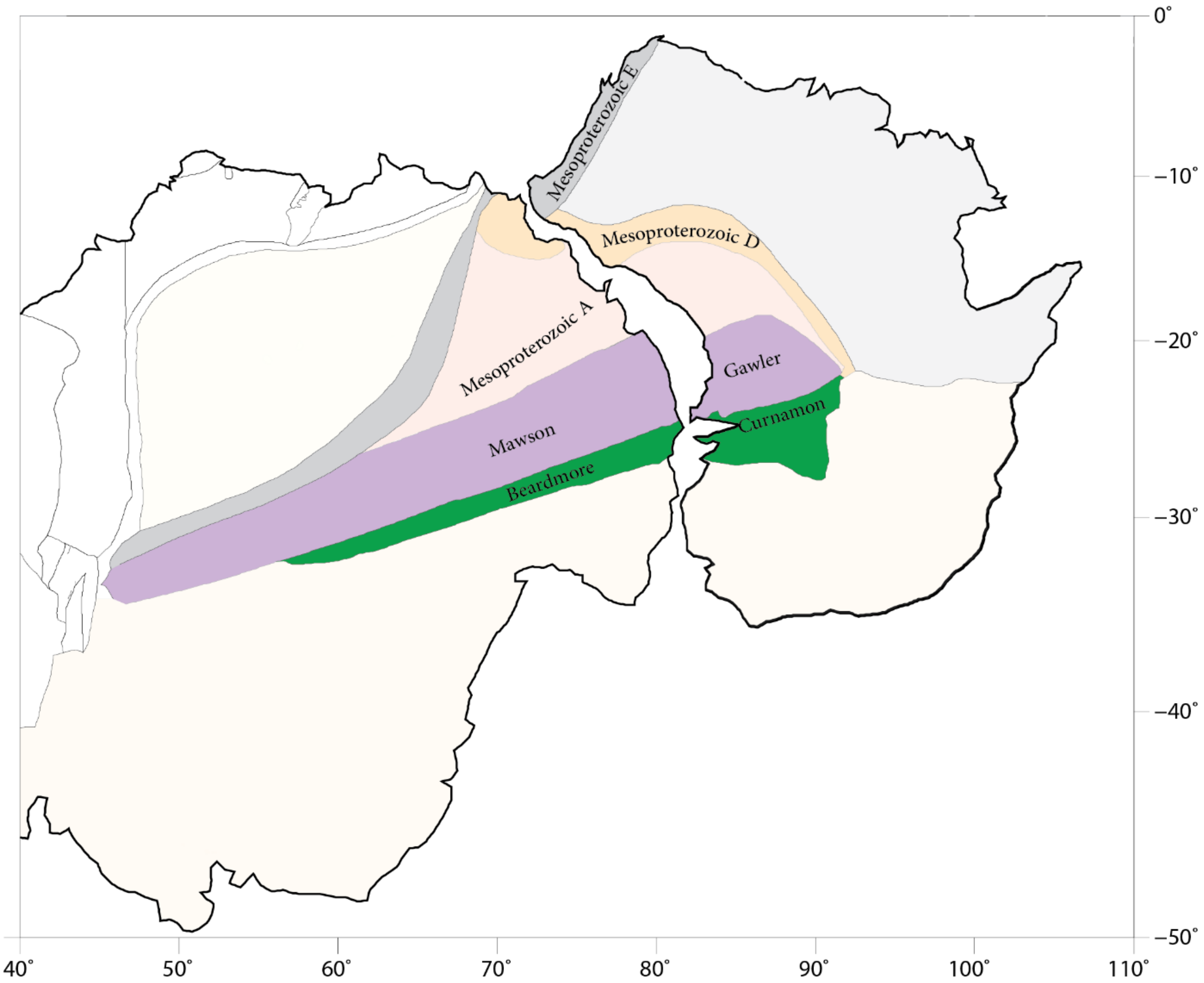


Figure 19: Map showing our reconstruction of Australia and Antarctica (with respect to Africa). Notice the alignment of the Beardmore and Curnamona cratons, and the continuation of the Mesoproretozoic rocks (Boger, 2011) between Antarctica and Australia. The legend for the Antarctic and India basements are same as figures 4 and 7.

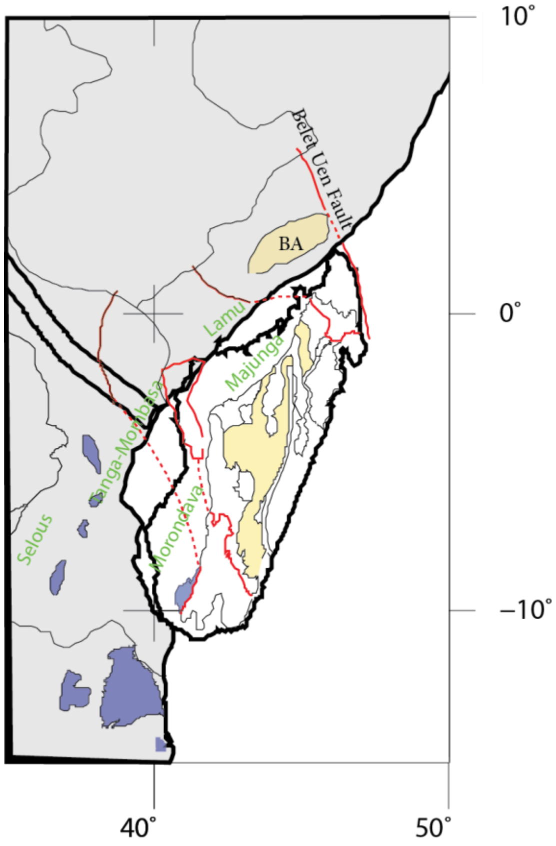


Figure 20: Map showing our reconstruction of Madagascar with respect to Africa. We propose the continuation of the Vohibory PanAfrican shear zone to the PanAfrican shear zone in Tanzania, the Brava fault in Kenya to continue with the Andreaparaty shear zone in Madagascar, and the Belet Uen fault in Somali to be continues with the fault lying to the northern fringe of Madagascar. BA= Bur Acaba.

Article submitted.

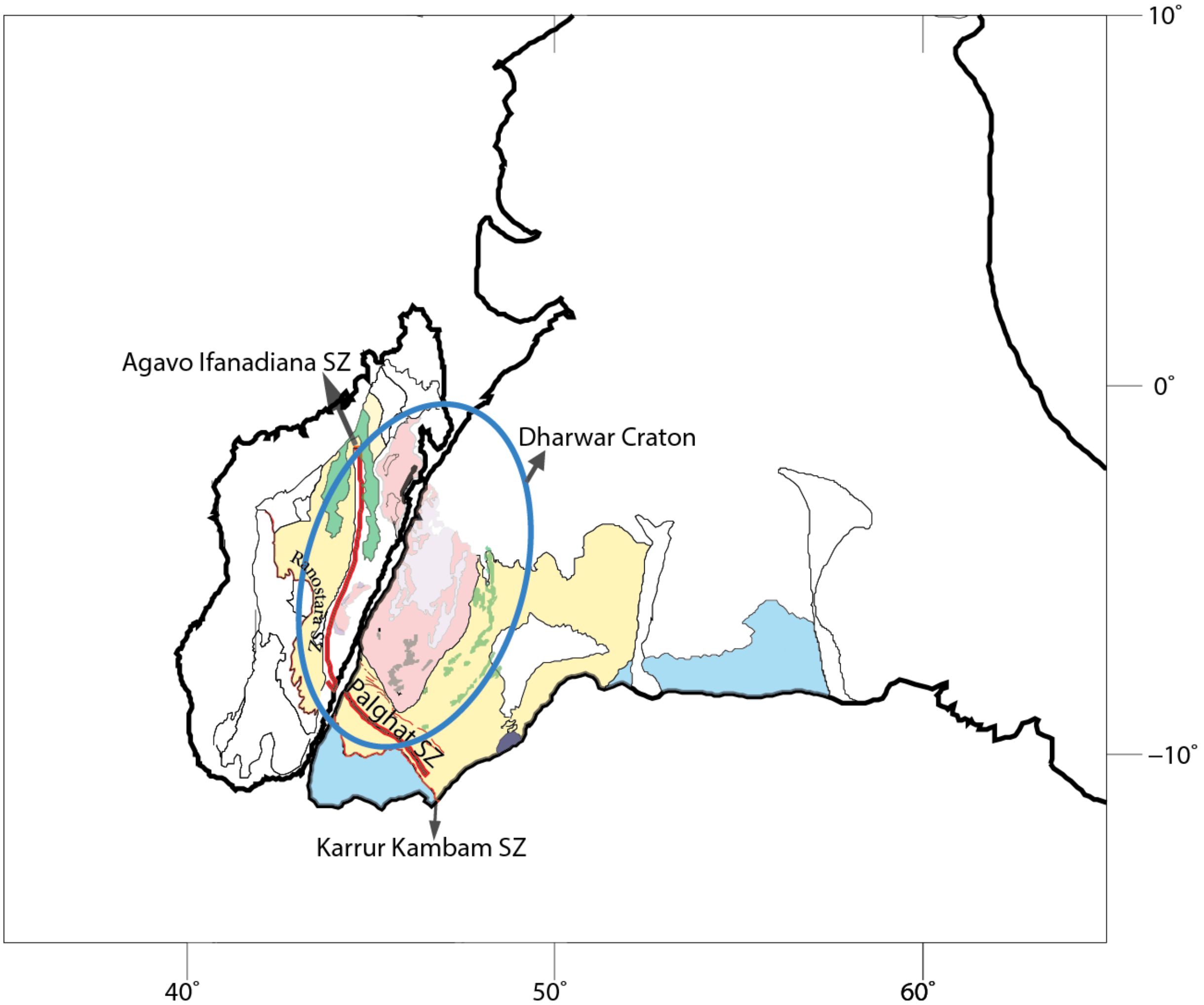


Figure 21: Map showing our reconstruction of India and Madagascar (with respect to Africa). Note the correspondence of Eastern Dharwar craton of India and the Archean rocks of Madagascar. We fit the Precambrian shear zones of Agavo Ifadiana and the Ranotsara shear zones of Madagascar to respectively the Palghat and to the Karrur Kambam shear zones of India. This ensures a perfect alignment of Archean and Mesoproterozoic rocks in both in Madagascar and India. The legend for the Madagascar and India basements are same as figures 6 and 8.

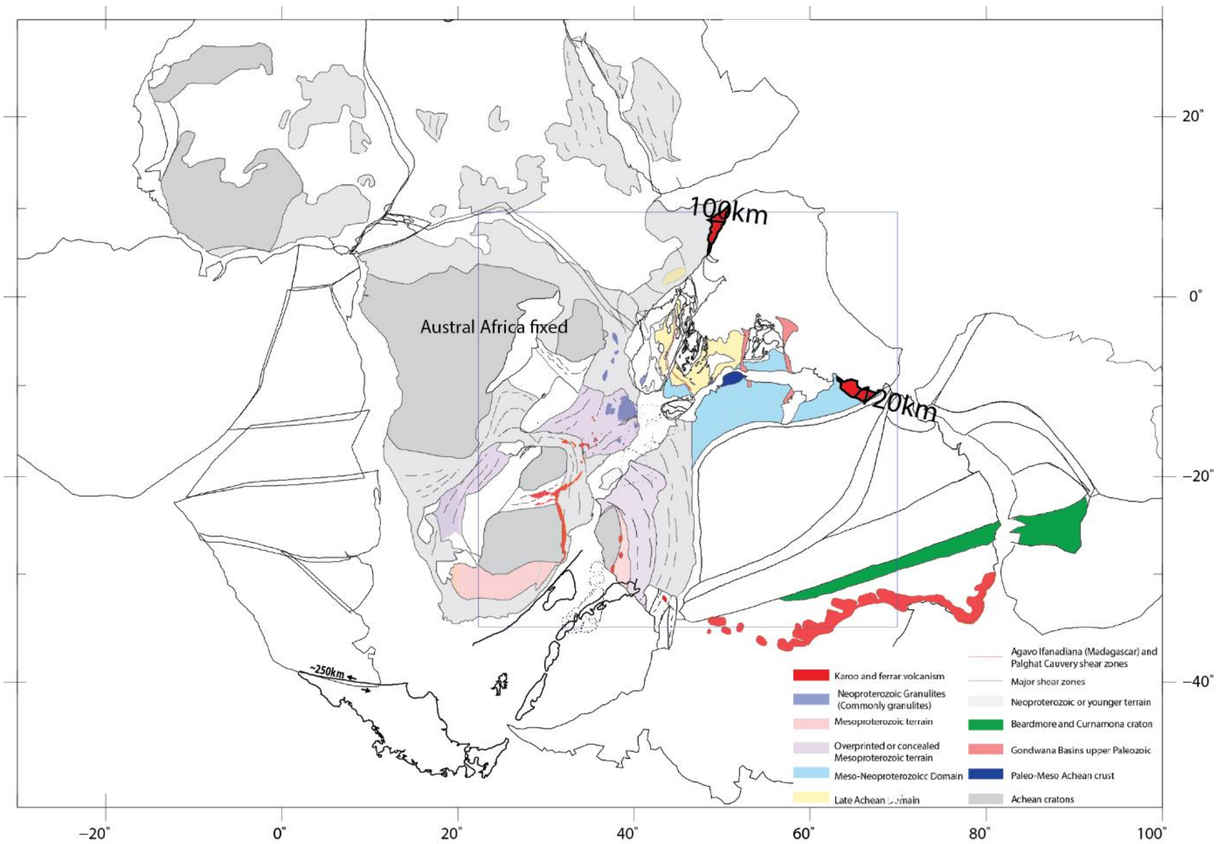


Figure 22: Our proposed initial fit of Gondwana. This new model shows the full extent of the Dharwar craton traced from the India plate into Madagascar and possibly into the Bur Acaba of Africa and beyond. It permits a very good alignment of the Beardmore and Mawson cratons in Antarctica and Australia, 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. 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

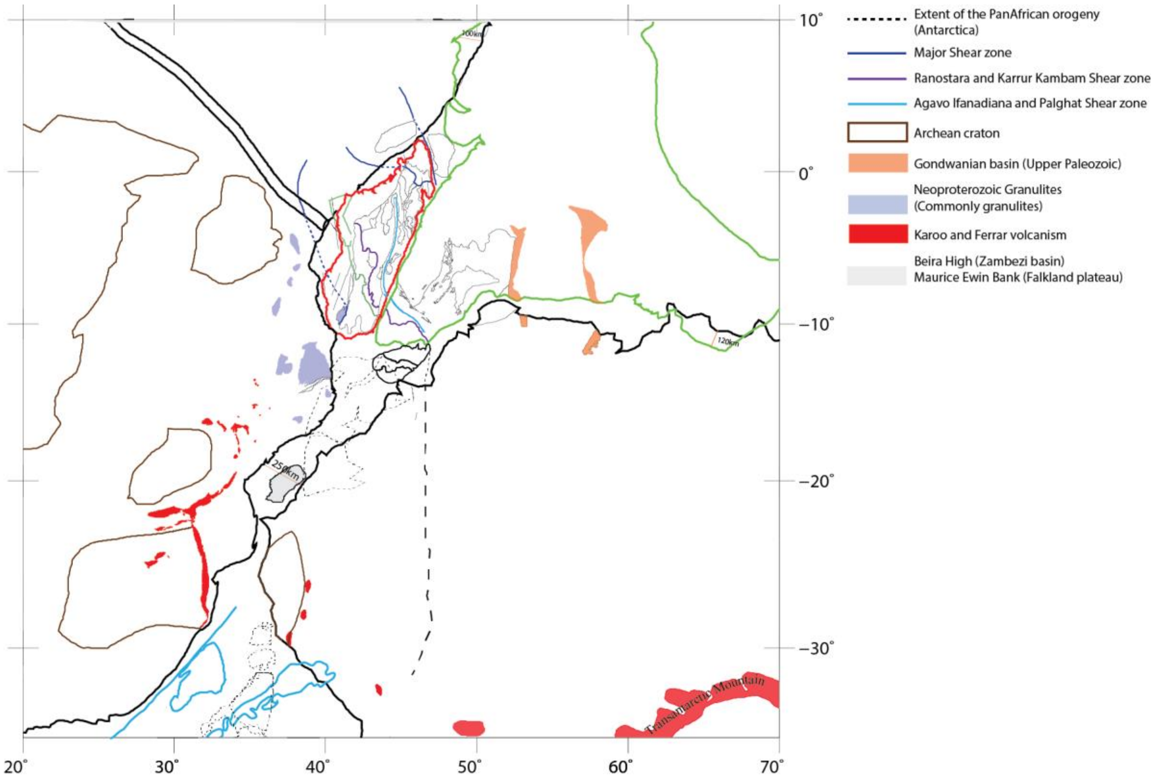


Figure. 23: Zoom on figure 22, showing perfect alignment of Precambrian shear zones of the Agavo Ifadiana and Ranostara shear zones of Madagascar, to the Palghat and Karrur Kambam shear zones of India respectively. It also shows the full extent of the PanAfrican orogenic event and the Karoo volcanism in Gondwana.

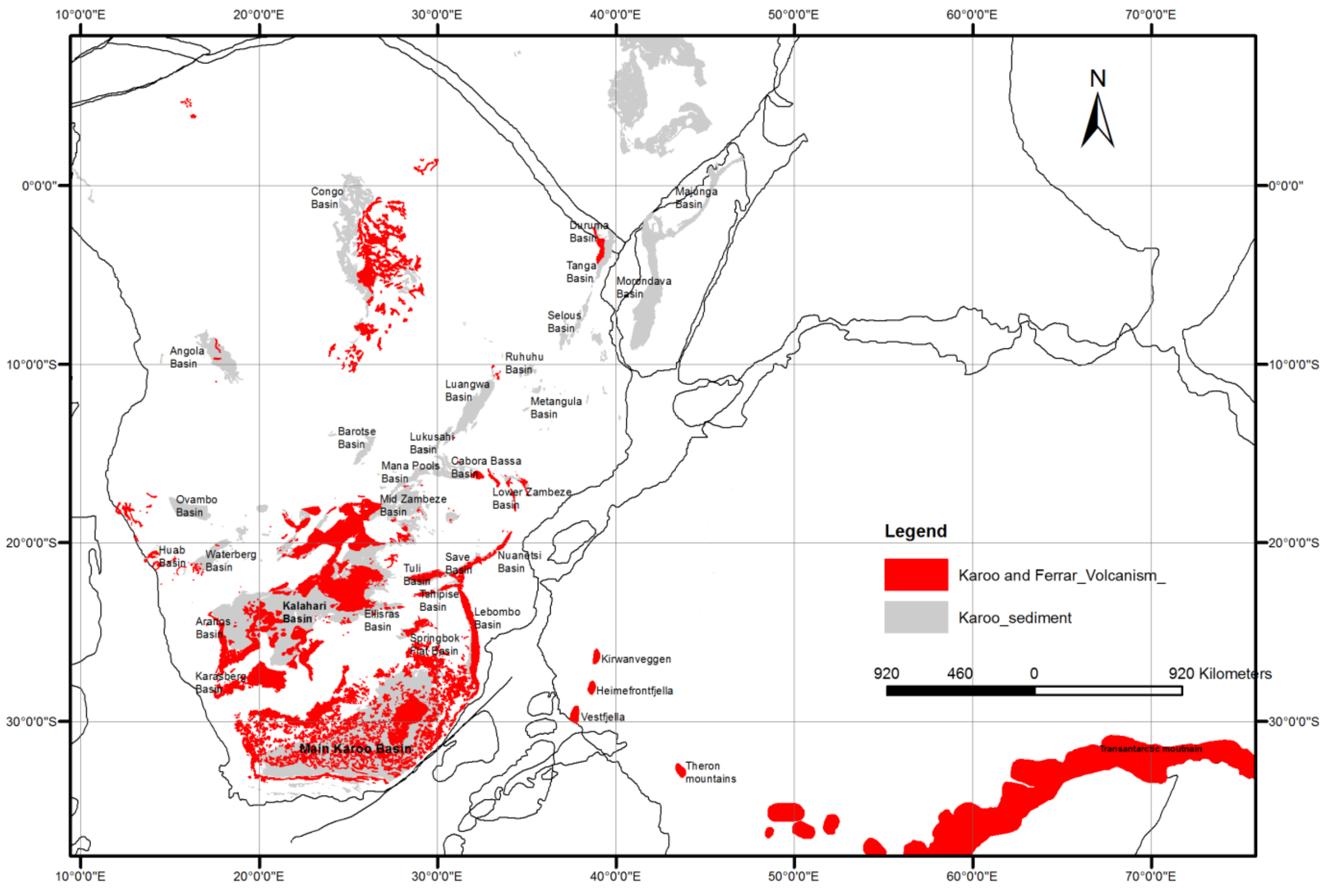


Figure. 24: New reconstruction model showing the main distribution of Karoo sediments and volcanics in Africa, Madagascar, and Antarctica. The Southern Africa continent is characterized by vast network of sills and dykes which are pre-syn-post Karoo volcanism. The outcrop of the Karoo volcanics and sediments in Africa and Madagascar is after Guillocheau and Liget (2009), Antarctica is After Elliot and Fleming (2004) and Jokat et al., (2003). World Geodectic System 1984.

INITIAL FIT POLES.

Tectonic Plate (All motions relative to Africa Austral)	Latitude	Longitude	Rotation
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.