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Interaction between magmatism and deformation at magma-rich rifted margins: the example of the Mozambique channel

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École doctorale des Sciences de la Terre et de l'Environnement (ED 413)
Institut de Physique du Globe de Strasbourg (UMR 7516)

THÈSE présentée par :
Simon TOMASI
soutenue le : 18 mai 2020

pour obtenir le grade de : Docteur de l'Université de Strasbourg

Discipline : Sciences de la Terre
Spécialité : Géologie Structurale

Interaction between magmatism and deformation at magma-rich
rifted margins:
The example of the Mozambique Channel

THÈSE dirigée par :

Pr. Gianreto Manatschal (Université de Strasbourg)

RAPPORTEURS :

Dr. Gwenn Péron-Pinvidic (Geological Survey of Norway)

Dr. Dieter Franke (Bundesanstalt für Geowissenschaften und Rohstoffe)

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Pr. Laurent Geoffroy (Université de Brest)

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Foreword

The study of rifted margins is one of the main focus of the GéOLS team at the Institut de Physique du Globe (IPG) at the University of Strasbourg. Although the focus of the research has been in the past on magma-poor rift systems, more recently it has been shifted to the study of magmatic processes linked to the evolution of rifted margins. This goes along with the discovery that the subdivision in volcanic vs. non-volcanic or magma-rich vs. magma-poor systems does not correspond to what can be observed in many rifted margins. This binary distinction fails when analysing in more detail magma-rich and magma-poor rifted margins that share more similarities than previously assumed.

Thus, in the research group, the study of magmatic systems has become of major interest in the last years, which is also the case for the entire academic community working at rift systems. Despite the many studies, magmatic processes related to rifting remain yet poorly understood. In particular when, where and how much magma is produced, and how it is emplaced during rifting remains little understood.

Therefore, this study aims to find first order answers to these questions based on the study of an extensive data set and using seismic interpretation and quantitative geophysical methods. This project was loosely connected, but not directly linked to a big project named "PAMELA" (Passive Margins Exploration Laboratories) launched in 2013 and financed by TOTAL/Ifremer. The PhD project was financially supported by TOTAL that also provided a dense seismic dataset of the study area. The mapping and investigation of this data set the foundation of this project, although, in its final version, only little of this data will be presented.

Résumé étendu

Introduction

Bien que l'étude des marges passives ait largement progressée, où, quand, et comment le magma intervient dans la formation de la marge, et comment estimer les volumes relatifs des additions magmatiques par rapport à la croûte originelle restent incompris. Il est cependant nécessaire de comprendre ces interactions pour restaurer le fit initial avant la rupture.

Dans cette étude, le système conjugué Mozambique-Antarctique dont l'ouverture est associée à l'action du plume Karoo-Bouvet sert de cas d'étude. Ce système permet d'analyser, par une double approche géologique et géophysique, la rupture de la lithosphère continentale liée à un plume et comment les processus magmatiques interagissent avec la déformation. Pour cela, cette étude répond à trois questions principales : comment restaurer des systèmes extensifs extrêmement impactés par le magmatisme ? Peut-on développer une méthode conjointe géologique et géophysique pour caractériser une croûte hybride (i.e. proportion de croûte continentale et addition magmatique inconnue) ? et en dernier lieu, comment peut-on distinguer et décrire simplement l'architecture au premier ordre des marges passives ?

Dans cette thèse, le premier chapitre vise à trouver le fit initial du système Mozambique-Antarctique impacté par le plume en utilisant différentes méthodes de reconstruction. Par la suite, une analyse géologique et géophysique de croûtes hybrides est réalisée par l'exemple des Plaines Côtières du Mozambique pour trouver les caractéristiques de ce type de croûte. En dernier chapitre, je propose seulement deux paramètres clés contrôlant le panel d'architecture magmatique observé dans les marges passives.

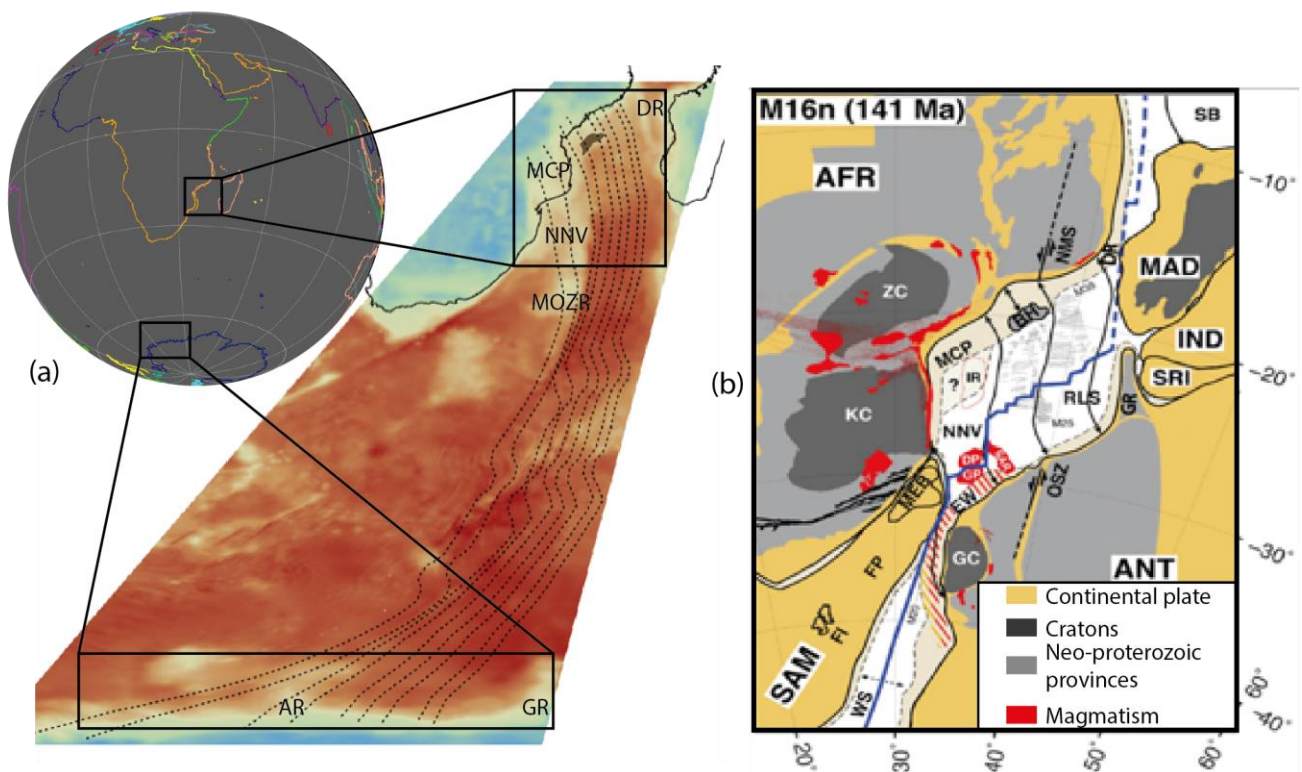


Figure 1: Le système conjugué Mozambique-Antarctique. (a) Carte de la bathymétrie avec les lignes de transport de Seton et al., 2012. (b) Reconstruction de Schimschal and Jokat, (2019). AFR: Afrique, ANT: Antarctique, IND: Inde, MAD: Madagascar, SAM: Amérique du Sud, SRI: Sri Lanka, DR, Davie Ridge, EW: Explora Wedge, FI: Falkland Islands, FP: Falkland Plateau, GC: Grunehogna Craton, GP: Galathea Plateau, GR: Gunnerus Ridge, IND: India, IR: Inharrime Ridge, KC: Kaapvaal Craton, MAD: Madagascar, MCP: Mozambique Coastal Plains, MEB: Maurice Ewing Bank, MozR: Mozambique Ridge, RLS: Riser Larsen Sea.

1. Le challenge pour restaurer des marges passives très riches en magma : L'exemple du système conjugué Mozambique-Antarctique

Comment s'effectue la rupture des lithosphères continentales en présence d'un plume est à ce jour peu compris. La première partie de la thèse se focalise sur une méthode permettant de restaurer des systèmes liés à des plumes par l'intermédiaire du système conjugué Mozambique-Antarctique (Figure 1) pour lequel de nombreux modèles cinématiques ont été proposés pour restaurer le fit initial. Le principal débat des dernières études concerne la nature crustale des domaines des Plaines Côtières et du Haut de Beira où certaines études proposent que ces domaines soient purement océaniques, ou purement magmatiques résultant en divers scénarios de restauration cinématique et avec des conséquences majeures pour l'évolution géologique de ce domaine.

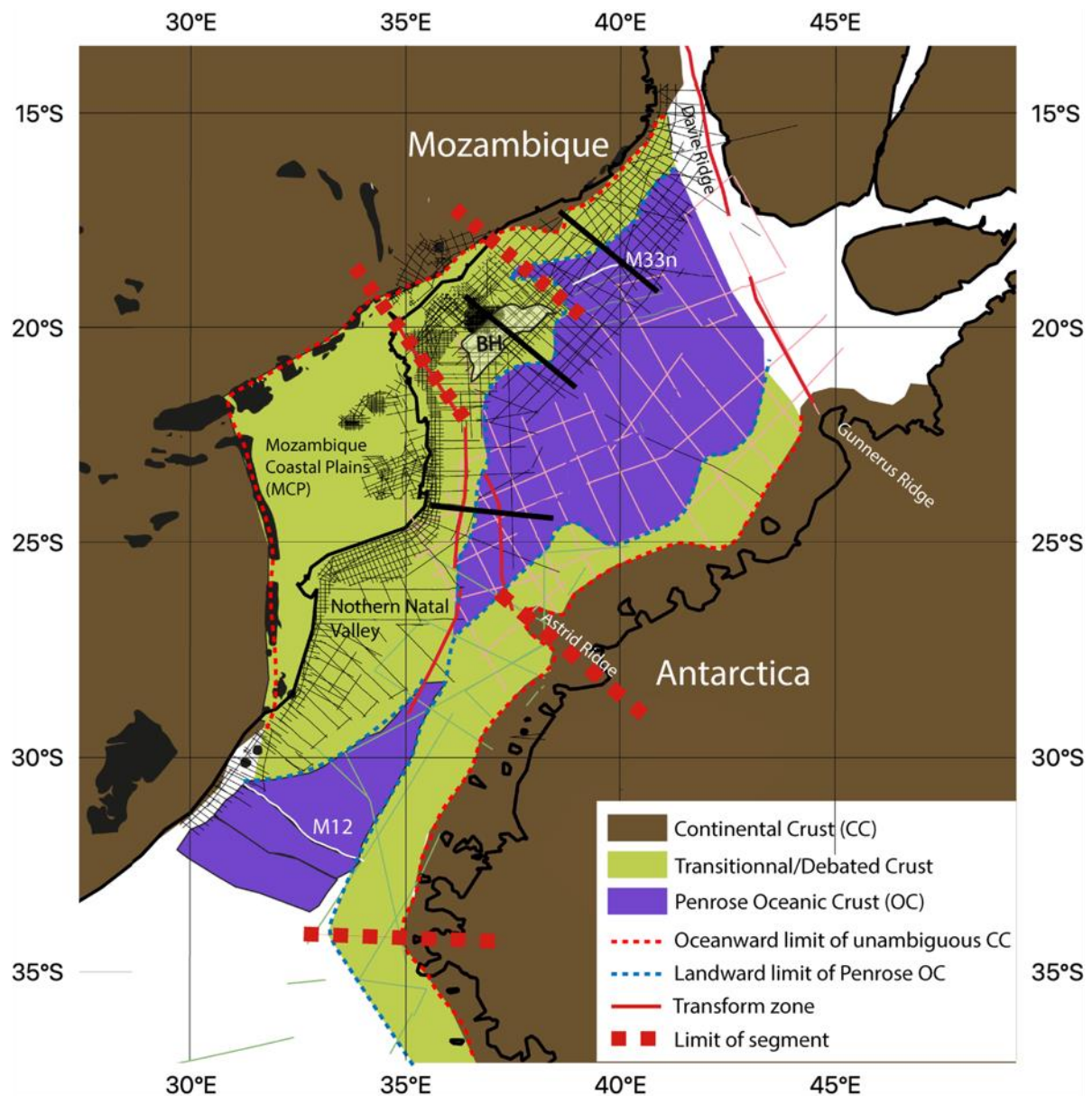


Figure 2: Carte du Canal du Mozambique à 140Ma (en utilisant les pôles de Davis et al., 2016) des domaines interprétés à partir des données de sismiques réflexion. Les données du Mozambique sont représentées par les lignes noires, les données Antarctique par les lignes rose et bleues.

Dans un premier temps, l'étude d'un dense jeu de données sismiques a permis de délimiter la limite du domaine continental certain et aussi la limite de la première croûte océanique identifiée. Cependant une zone, entre ces deux limites, reste incertaine quant à sa nature (Figure 2). Une méthode de test de scénarios antithétiques considérant cette zone soit en tant que purement continental, soit en tant que purement océanique a été expérimenté (Figure 3). Cette approche a clairement mis en évidence qu'aucun des scénarios ne peut être envisagé pour obtenir un fit initial en restaurant la déformation. Il est donc nécessaire de se tourner vers un scénario compromis alliant croûte continentale et addition magmatique.

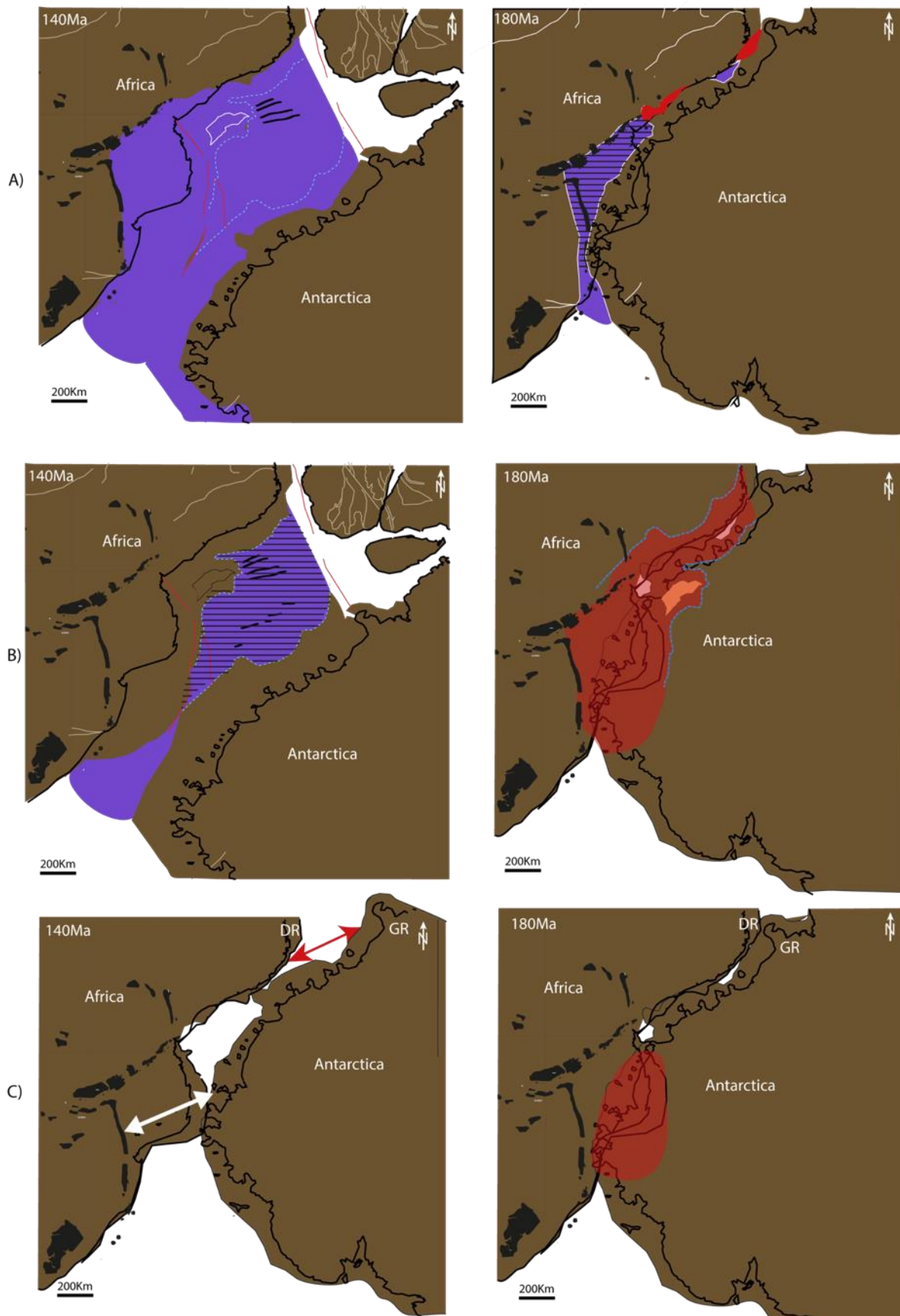


Figure 3: Test de scénarios en utilisant les pôles de Seton et al. 2012 . A) scénario où le domaine transitionnel est entièrement magmatique. B) Scénario où le domaine transitionnel est entièrement continental, C) scénario avec un mouvement initial vers le NE de l'Antarctique par rapport à l'Afrique fixe DR : Ride de Davie, GR : Ride de Gunnerus. Les superpositions de croute continentale sont affichées en rouge, les domaines qui ne sont pas restaurés sont affichés par des hachures.

Dans un deuxième temps, une première approche quantitative est proposée pour estimer l'épaisseur/volume des additions magmatiques et ainsi la proportion relative entre croûte continentale et magmatique. Une reconstruction au moment de l'ouverture en considérant les épaisseurs crustales de la région Mozambique et de la région Antarctique montre clairement des zones d'anomalies d'épaisseurs crustales (Figure 4).

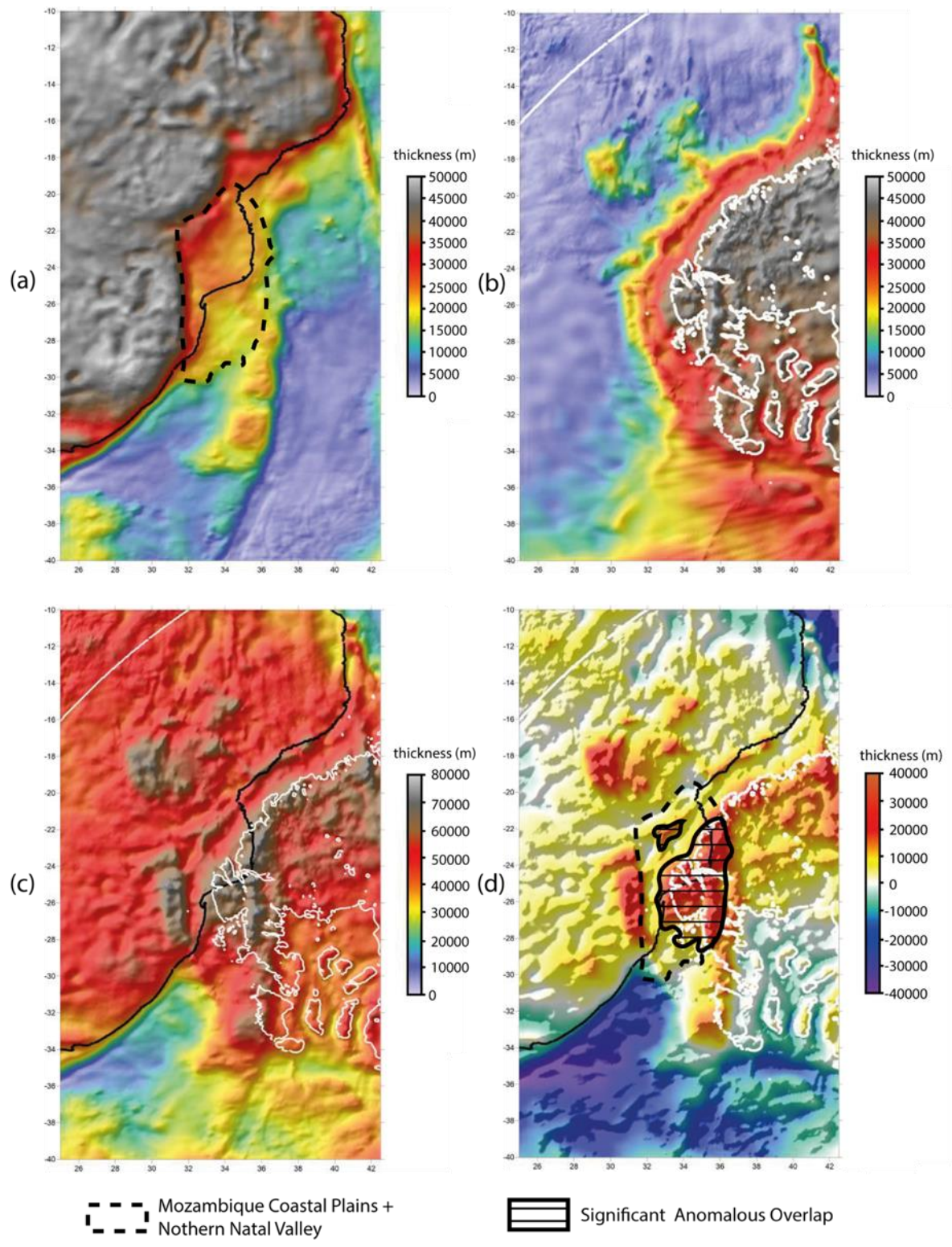
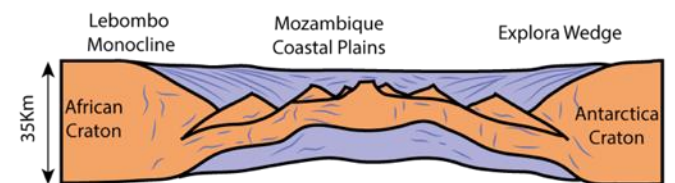
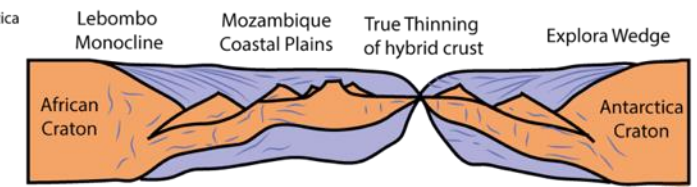
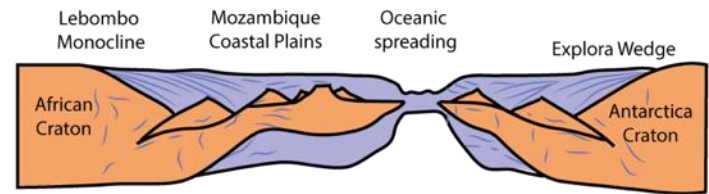
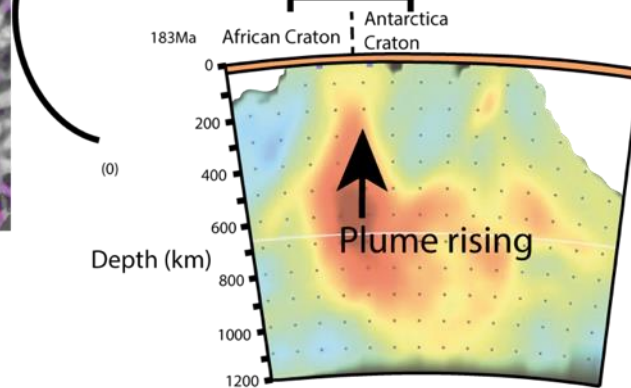
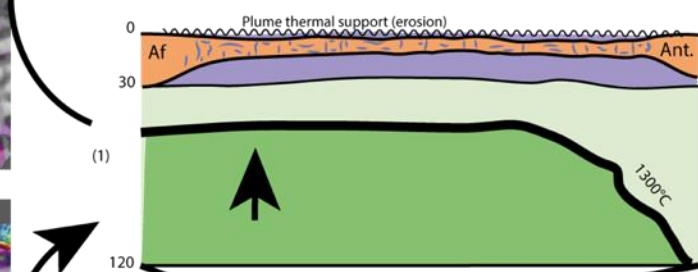
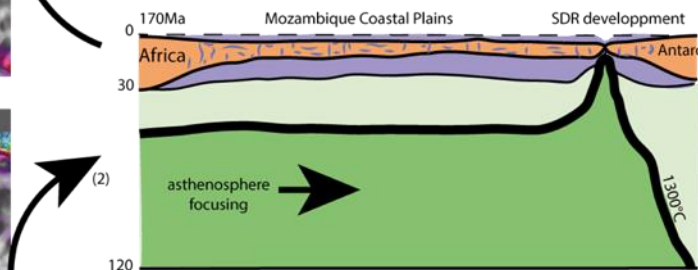
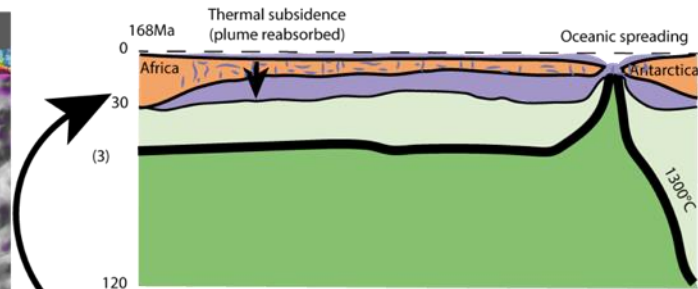
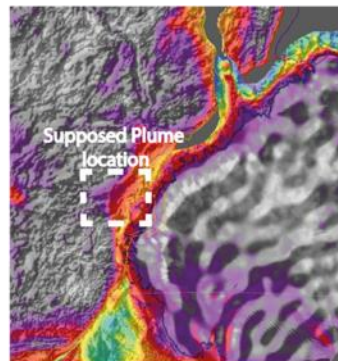
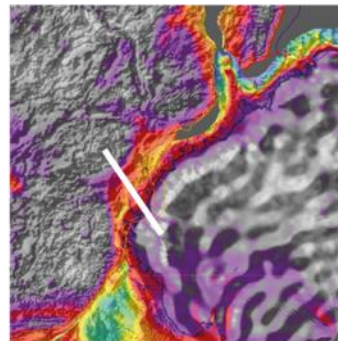
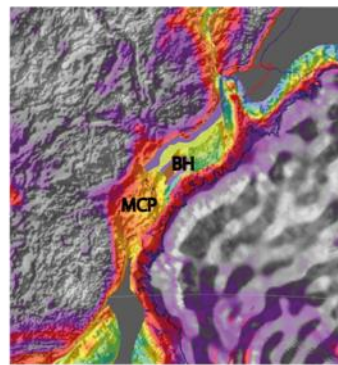


Figure 4: (a) Carte d'épaisseur crustale de la marge Mozambique (issue d'inversion gravimétrique à partir de données publiques). Les domaines des plaines côtières du Mozambique et la Vallée nord du Natal sont délimités par les Lignes pointillées; (b) Carte d'épaisseur crustale de l'Antarctique restaurée à 177Ma (Afrique fixe, en utilisant les pôles de rotation de Müller et al., (2008)); (c) Superposition des deux cartes d'épaisseur crustale (a)+(b); (d) carte d'anomalie (c)-44.5km où 44,5 représente l'équivalent de l'épaisseur crustale d'une croûte continentale plus celle d'une croûte océanique.

Ainsi, je prends en compte ces ordres de grandeur lors de l'interprétation des lignes sismiques et propose une interprétation finale des lignes cohérente avec les restaurations des deux marges. Enfin, un nouveau modèle d'évolution du système Mozambique-Antarctique en 3 étapes est proposé (Figure 5) :

- 1) Due à l'activité du plume, l'amincissement de la croûte continentale est associé à un apport continu de matériel magmatique qui compense l'amincissement en remplissant les bassins créés. Ainsi, l'épaisseur de la croûte hybride (croûte continentale + addition magmatique) reste constante. La croûte hybride est difficilement identifiable car cette croûte est mal-imaginée par la sismique réflexion et donc la proportion d'addition magmatique est difficile à discerner.
- 2) L'amincissement de la croûte continentale se focalise, l'apport magmatique ne compense plus l'amincissement. L'épaisseur de la nouvelle croûte hybride diminue drastiquement. Des SDR peuvent alors se former. L'apport magmatique et la déformation sont localisés.
- 3) Le budget magmatique se stabilise et reste focalisé, et le régime d'océanisation se met en place.

Figure 5 (voir page suivante): Évolution schématisée du système extensive Mozambique - Antarctique (0) Image tomographique utilisée ici pour illustrer l'échelle de grandeur d'un plume d'après Koptev et al., 2015. (1) Le plume remonte, la production de magma commence alors que la lithosphère s'amincit. Les additions magmatiques maintiennent la croûte à une certaine épaisseur compensant ainsi l'amincissement crustal. (2) Fin du pulse magmatique, des SDRs peuvent se développer. (3) Break-up lithosphérique et début de l'océanisation. Les cartes indiquent les étapes de reconstructions associées. Les interprétations crustales sont inspirées de Foulger et al., (2019).



2. Une analyse géophysique de « croûte hybride » dans des rifts associés à un plume.

La caractérisation des croûtes hybrides associées à des plumes est difficile à cerner par l'interprétation de données sismiques car le magmatisme extrusif empêche une belle imagerie en profondeur et, par conséquent, des possibilités d'interprétation très variées. Dans cette étude, les exemples du Haut de Beira et des Plaines Côtières du Mozambique sont analysés puisque leurs socles sont maintenant considérés comme des croûtes hybrides.

Dans cette étude, nous utilisons l'inversion gravimétrique d'une part en utilisant des données de sismique 2D de bonne résolution spatiale pour obtenir une carte précise de l'épaisseur sédimentaire de la marge du Mozambique. Dans un deuxième temps, nous utilisons les interfaces de bathymétrie, toit du socle, et Moho issues de sismique réfraction de l'IFREMER (Figure 6). L'inversion gravimétrique permet de mettre en évidence un amincissement rapide de la croûte dans la partie est du bassin du Mozambique. Une analyse de subsidence est également faite pour comprendre le rôle du support thermique d'une croûte hybride lors de sa formation (Figure 7).

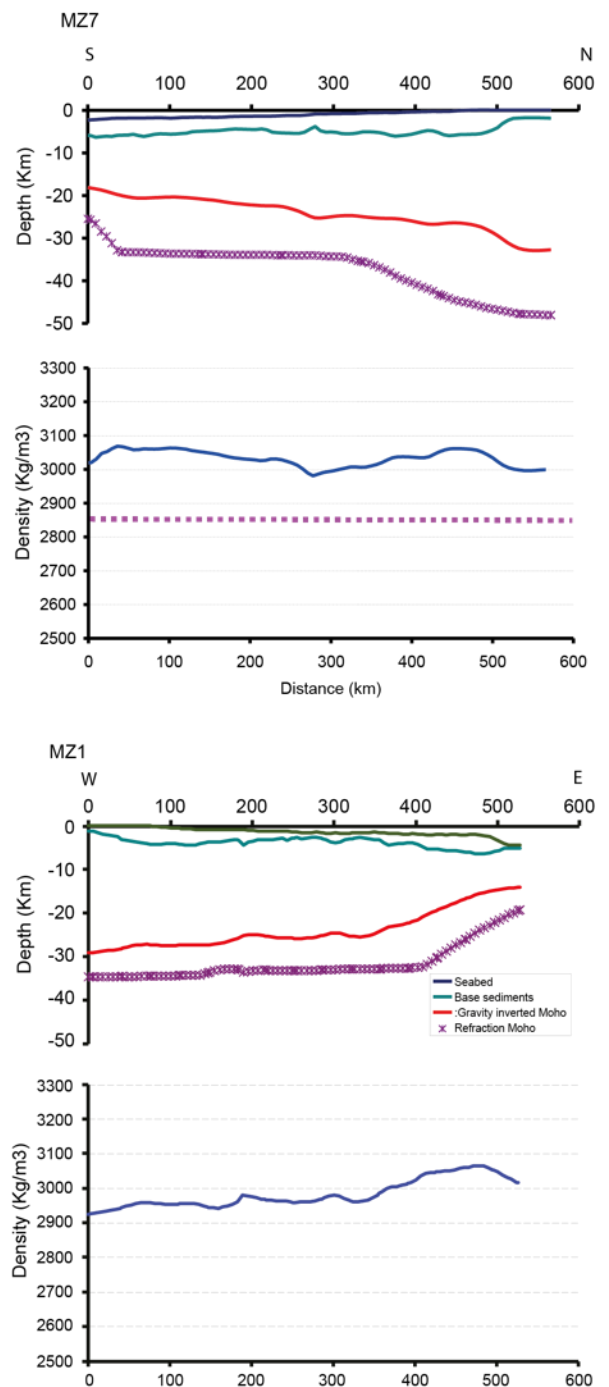


Figure 6: Résultat de l'inversion gravimétrique jointe comparant le Moho de l'inversion gravimétrique et le Moho de la réfraction sismique. Pour établir le fit entre les deux Moho, il faut ajuster les densités dans la croûte. Le résultat de ces changements de densité sont affichés en dessous de la coupe montrant les différentes interfaces.

Le haut de Beira présente une épaisseur d'environ 25km avec des densités de croûte qui ne permettent pas de déterminer la nature de la croûte (possiblement croûte continentale avec de lourdes intrusions). Concernant les Plaines Côtières du Mozambique, une croûte hybride de 25 à 30km d'épaisseur relativement constante. Les densités de la croûte du Limpopo anormalement élevées révèlent la présence potentielle de matériel mafique lié à la production magmatique par décompression lors de l'action du plume. Ce matériel à la fois extrusif et intrusif à forte densité contribuerait à plomber la croûte et augmenter la densité moyenne. L'analyse de subsidence montre que ces lithosphères sont affectées par un support thermique dans un premier temps, puis la subsidence thermique permet de créer

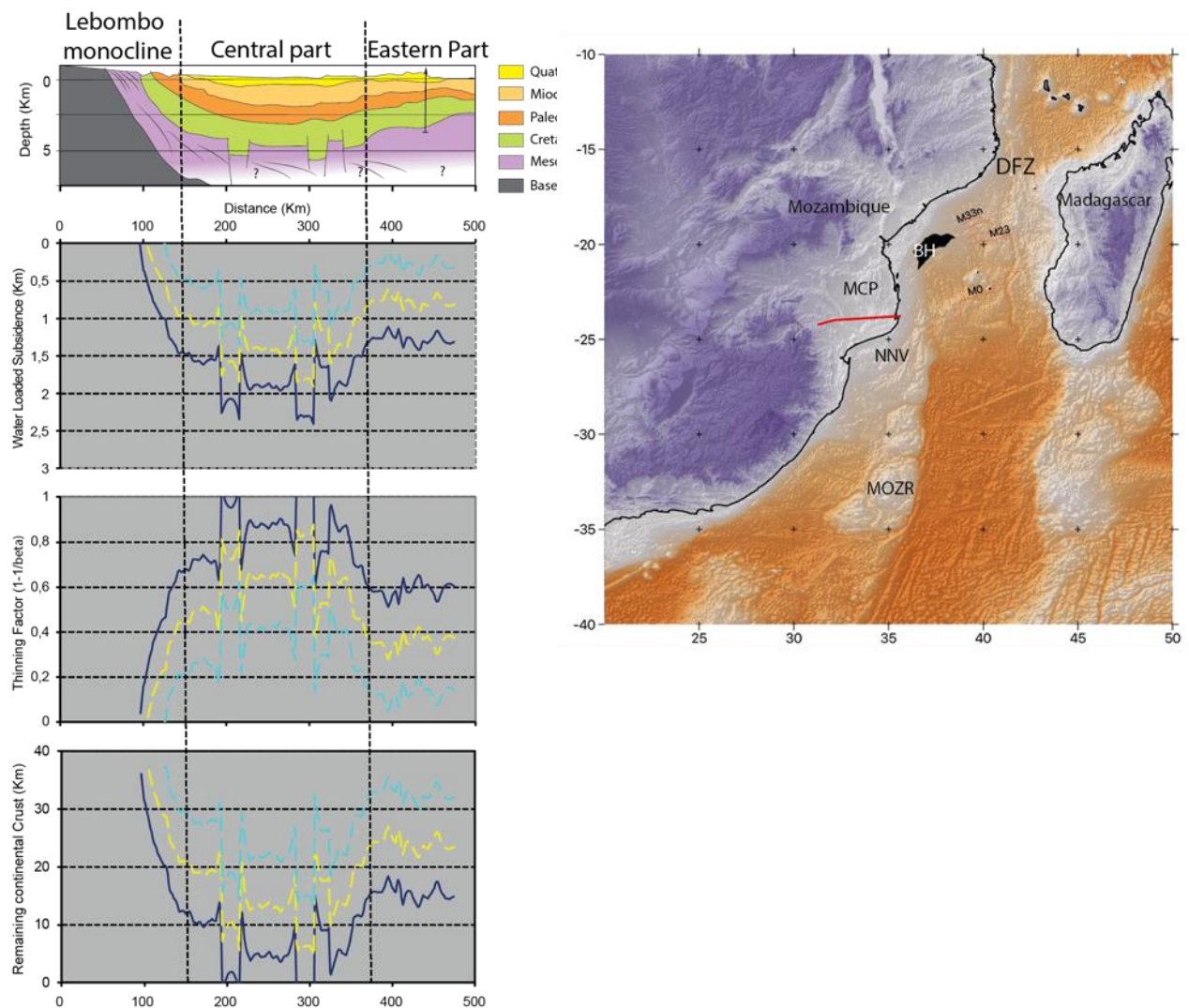


Figure 7: Résultat de l'analyse de subsidence à partir de la section de Davison et al., 2017. La localisation de la ligne est affichée en rouge sur la carte. La courbe bleu clair représente un support thermique de 0m. La courbe jaune représente un support thermique de 500m. La courbe bleu foncé représente un support thermique de 1000m.

un bassin même sur une croûte relativement épaisse.

En conclusion, les résultats montrent que les croûtes hybrides sont donc caractérisées par une épaisseur qui est due à l'ajout de matériel magmatique qui compense l'extension, une densité relativement élevée liée au plombage de la croûte par du matériel mafique et enfin un régime thermique particulier par le support thermique, dans un premier temps, et par la suite, la subsidence thermique.

3. Les principaux paramètres contrôlant l'architecture des marges : le timing et le budget magmatique.

L'étude récente des marges passives remet en question la catégorisation des marges entre pauvre en magma et riche en magma. Dans cette dernière partie, je génère un panel d'architecture par un simple outil créant des marges thermiquement équilibrées selon un certain facteur beta (β) et dans lequel nous varions uniquement deux paramètres (voir Figure 8): (1) l'arrivée du magmatisme, c'est à dire quand le magma arrive-t-il par rapport à une arrivée normale (facteur d'amincissement = 0.54) et (2) le budget magmatique qui sera au final ramené à un budget de croûte océanique stable (6 ± 1 km).

Nous arrivons ainsi à reproduire les architectures premier ordre de l'ensemble des marges passives monophasées. Dans le modèle neutre, la déformation responsable de l'amincissement et le magmatisme sont légèrement superposés. Du magmatisme syn-tectonique doit être observé. Ces marges peuvent être l'équivalent des marges modérées en magma. Lorsque le budget est relativement faible par rapport au modèle neutre, et l'arrivée tardive, j'observe une zone d'exhumation mantellique. L'amincissement et les processus magmatiques ne sont pas superposés et clairement séparés par cette zone d'exhumation (e.g. marges ibériques, marge Sud-Est indienne, marges angolaises). Le retard de l'arrivée magmatique peut être due à l'héritage d'un manteau appauvri. Lorsque le magmatisme arrive tôt et le budget est élevé, le magmatisme peut possiblement arriver avant même que l'amincissement ait commencé. La déformation et le magmatisme sont des événements clairement superposés. Le magmatisme peut compenser l'extension dans les marges ultra-riches en magma associées à l'activité d'un plume (e.g. Santos, Mozambique, Ian Mayen).

Il paraît donc possible de décrire l'architecture des marges monophasées, au premier ordre, uniquement par le timing d'arrivée du magmatisme et son budget.

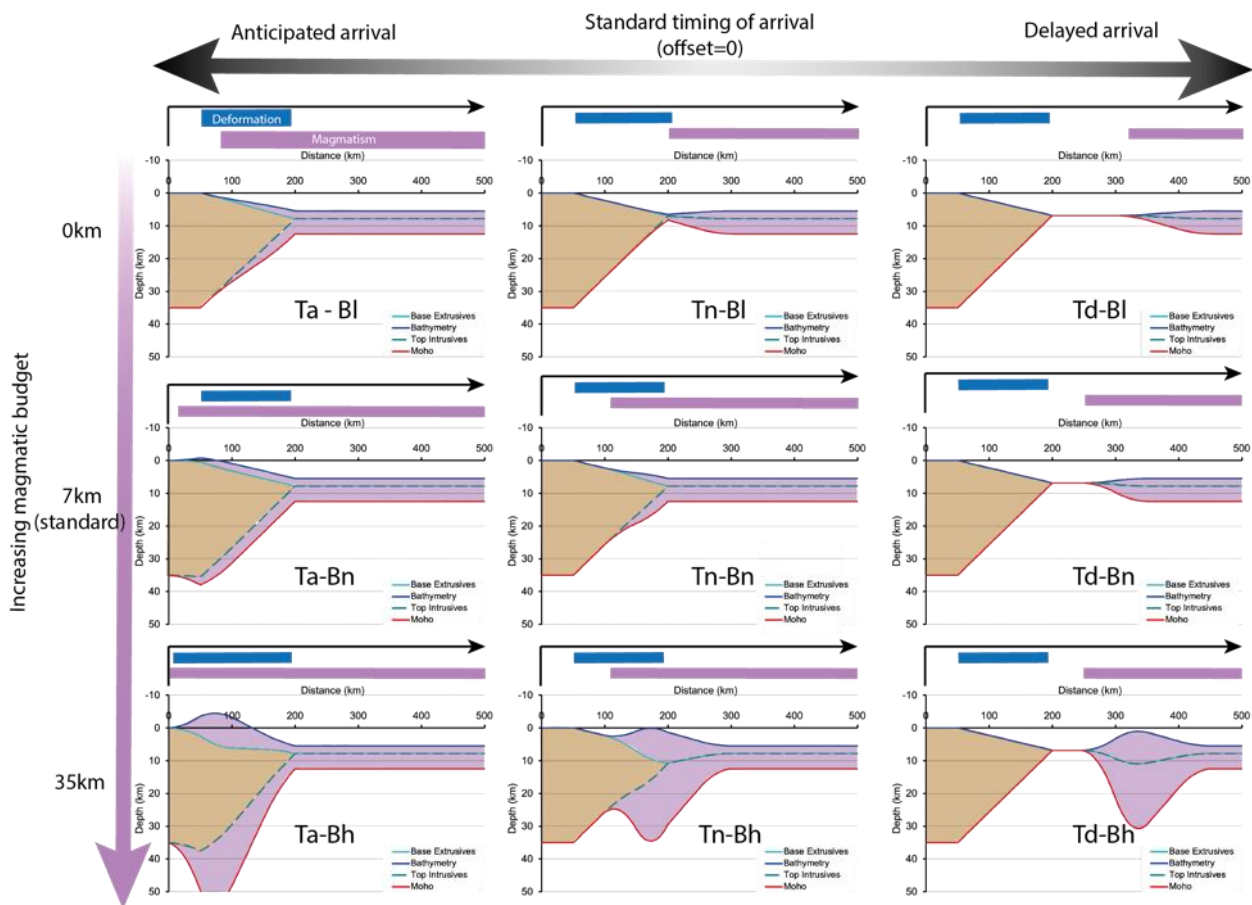


Figure 8: Marge équilibré résultant d'un modèle. L'axe horizontal tout en haut représente le timing relatif d'arriver du magma comparé au standard. L'axe vertical représente le budget magmatique initial. En brun est représenté la croûte continentale et en violet est représenté le magmatisme. Le diagramme au-dessus de chaque marge montre le timing relatif de la production magmatique (violet) par rapport à l'amincissement crustal (bleu).

Conclusion

L'étude des marges riches en magma associées à un plume par l'analyse de l'exemple des marges conjuguées Mozambique-Antarctique a permis de mettre en évidence les caractéristiques de croûtes hybrides (croûte continentale + addition magmatique en proportion inconnue). Ces domaines de croûte hybride empêchent des interprétations et des reconstructions régionales simples. Une méthode proposée par des test de scénarios est une première approche pour quantifier ces additions magmatiques et, finalement, proposer un scénario optimal pour reconstruire le fit initial. Par une seconde analyse géophysique, je mets en évidence les fortes densités crustales des croûtes hybrides, ainsi qu'une épaisseur anormalement élevée. D'autre part, la subsidence de ces domaines est également

caractéristique et témoigne d'un support thermal lié au plume. Enfin nous proposons que l'architecture, au premier ordre, de l'ensemble des marges monophasées, puisse être décrite par seulement deux paramètres : le timing d'arrivée du magmatisme et son budget.

Par conséquent, ce travail apporte de nouvelles méthodes pour étudier les systèmes en extension et les interactions avec le magmatisme et aussi un nouveau point de vue sur l'interprétation au premier ordre des marges passives.

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Chapter I: Introduction

1. Magmatism at rifted margins

1.1. State of the art

For more than two decades, rifted margins have been classified as either volcanic vs. non volcanic (Geoffroy, 2005). More recently and thanks to the access to better data, observations showed the presence of magma in so called non-volcanic margins, which lead to the use of magma-rich vs. magma-poor rifted margins (Franke, 2013; Gillard et al., 2017). Such classifications are, however, mainly based on the magmatic budget and on specific structural/architectural features, such as the presence or absence of Seaward Dipping Reflector (SDR) sequences and/or the presence of a faulted top-basement. Tugend et al., (2018) proposed that the interpretation of margins should not be limited to the magmatic budget only, but should also include the relative timing when magma is formed during rifting. These authors demonstrated, however, that for most rifted margins it remains difficult to define when and how much magma is emplaced in rifted margins and, apart from the classical SDR, to characterize syn-tectonic sequences.

The occurrence of magmatism in extensional systems complexifies the interpretations for several reasons. First and most important, even the best imaging techniques can't at present resolve and distinguish between intrusive magmatic additions and inherited, extended crust. Moreover, drilling is limited at depth and except few drill holes, the magmatic record related to rifting is difficult to untangle. Last but not least, modelling of magmatic systems is difficult, and apart for some very recent exceptions (e.g. Koptev et al., 2016; Tian and Buck, 2019), they remain rare. In contrast to the modelling of magma-poor systems, modelling magma-rich systems is hampered by the lack of codes and/or computing capacities, but also by the lack of conceptual understanding of how magmatic systems interact with tectonic systems during lithospheric breakup and are extracted from the mantle towards the surface or seafloor.

1.2. Magma-rich rifted margins

1.2.1. From concepts to observations (evolution of concepts/models)

Historical evolution of magma-rich rifted margins

The first time magmatic margins and the related SDRs have been described was by Mutter et al., (1982) of the Norwegian margin in seismic sections, where the authors observed a “layered acoustic stratification”. The authors suggest that these wedges formed at the very beginning of the basin genesis.

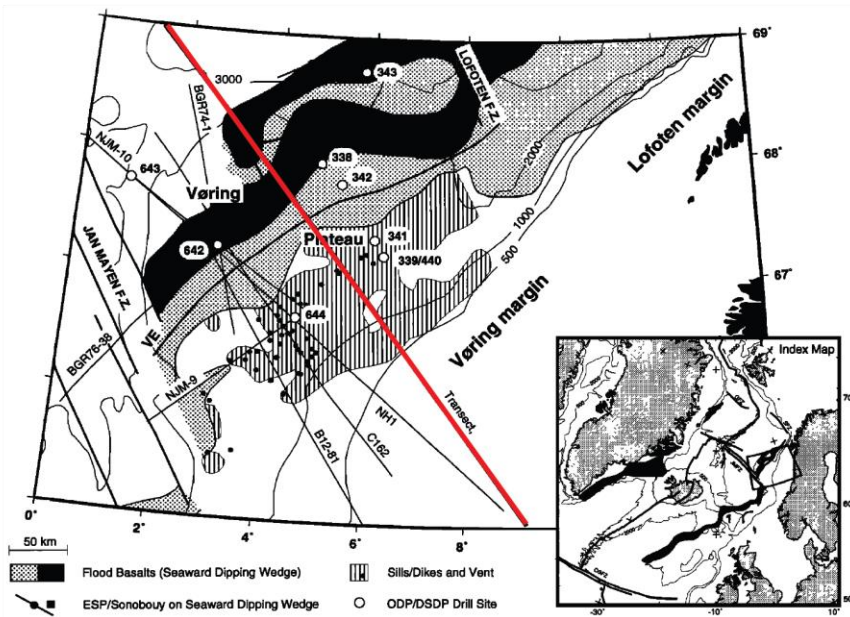
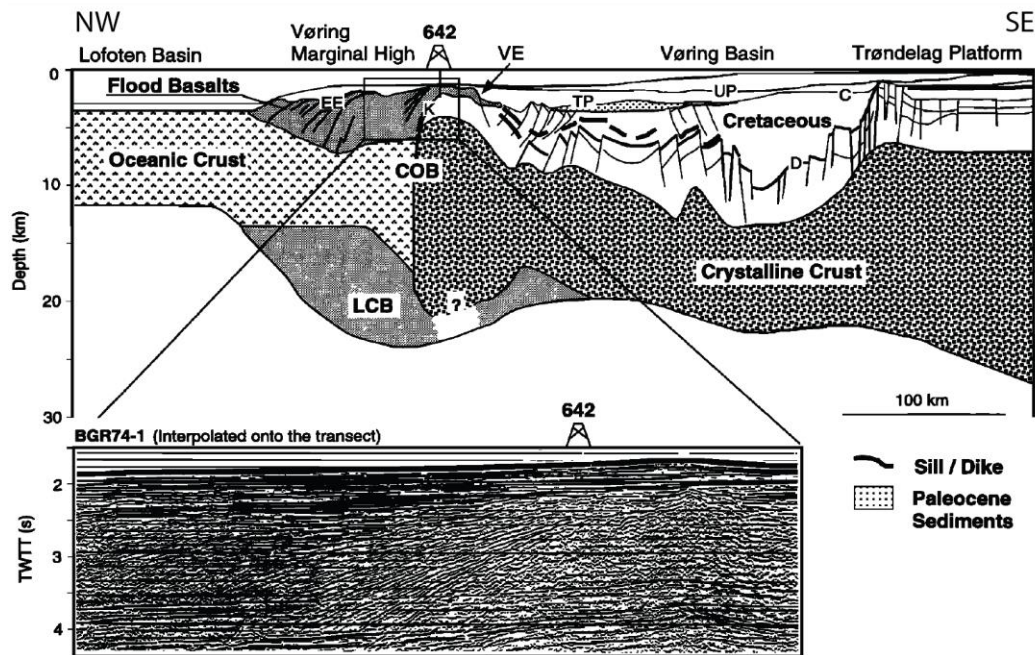


Figure 9: Interpretation of the Vøring margin, showing the SDR downlapping onto oceanic crust and the occurrence of a Lower Crustal Body (LCB) that under and overlie the Continent Ocean Boundary (COB) from Blomk and Eldhølen (1994)

Studies of rifted margins in general and of magma-rich systems in particular are difficult due to the lack of direct geological observations and the lack of good geological analogues. However, ODP drilling (ODP Legs 152, Site 918; DOP sites 642, 643, Eldholm et al., 1989, see Figure 9) allowed the access to rocks derived from SDR sequences, which enabled to develop a first model (Planke and Eldholm, 1994) that was refined by (Saunders et al., 1994; Geoffroy, 2001, 2005) and more recently (e.g. Geoffroy et al., 2015; Chauvet et al., 2019, see Figure 10) using drill hole data, field observations and seismic data.

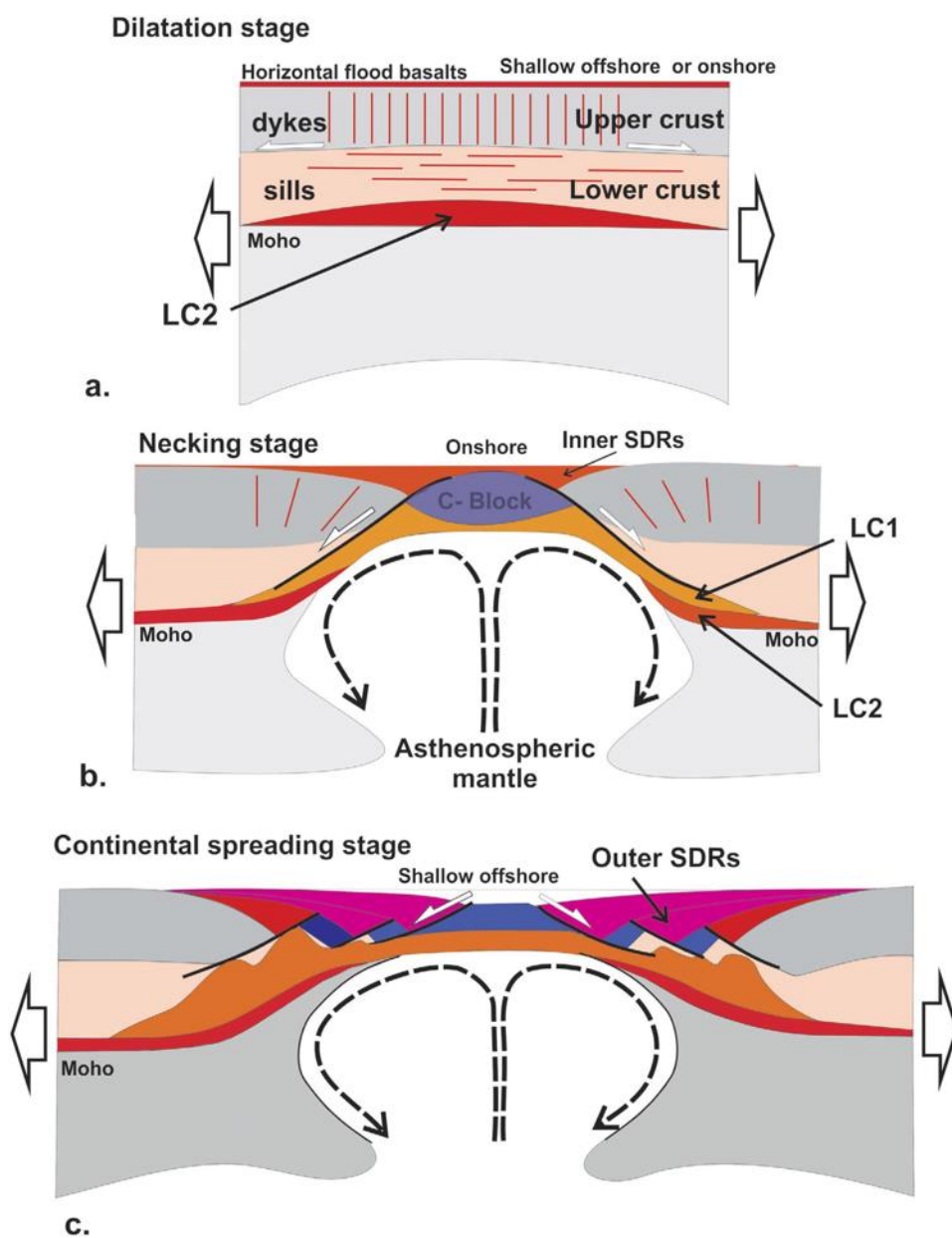


Figure 10: Model of formation of magma-rich margins (after Geoffroy et al., 2015). (a) initial stage: minor tectonic deformation; (b) crustal thinning: formation of inner SDR; (c) Continental spreading and fragmentation of the C-block.

At the margin scale, the most important observation is the increase of the magmatic budget toward the oceanic crust, the occurrence of SDRs, the smooth top basement and the down stepping onto oceanic crust (Geoffroy, 2005). A more global comparison of magma-poor and magma-rich rifted margins has been presented, using examples, by (Franke, 2013, see Figure 11), which highlighted the main differences between the two endmember type margins. Moreover, Franke (2013) also described and discussed the relation of rift propagation as a function of the plume location and defined magma-rich margins as margins where lithospheric thinning is linked to excess magmatic production. A key observation, well documented by Stica et al., (2014), is the migration of tectonic and magmatic activity towards the future steady state spreading centre that results in an oceanward younging of tectonic and magmatic processes at magma-rich margins. The proximal part is marked by relatively minor visible tectonic faulting but debates exist concerning faulting responsible of the wedging of the SDR (see SDR section thereafter).

Fundamental questions that remain in magma-rich rifted margins are where and how the crust is thinning. Answering to these questions is challenged by the fact that crustal thinning processes are masked by magmatic processes. Most studies focused on the magmatic processes and linked magmatic rifted margins to plumes (Hopper et al., 2003; Franke, 2013) and/or thermal anomalies within the lithosphere.

More recent studies recognized, however, that many magma-rich margins are defined by a magma-rich breakup, but can have a magma-poor precursor history such as shown for the N-Atlantic (Péron-Pinvidic and Osmundsen, 2016), the South Atlantic (Paton et al., 2017) or the NW Shelf in Australia (Belgarde et al., 2015). In such examples, the early evolution prior to magma-dominated breakup can be similar to that of magma-poor margins, i.e. includes stretching, necking and hyperextension (Peron-Pinvidic and Osmundsen, 2016). In most rifted margins, magma seems to form during the necking stage, in which case the breakup tends to be abrupt and the margin width is narrow. However, wide magma-rich rifted margins can also be observed (e.g. Pelotas, Stica et al., 2014).

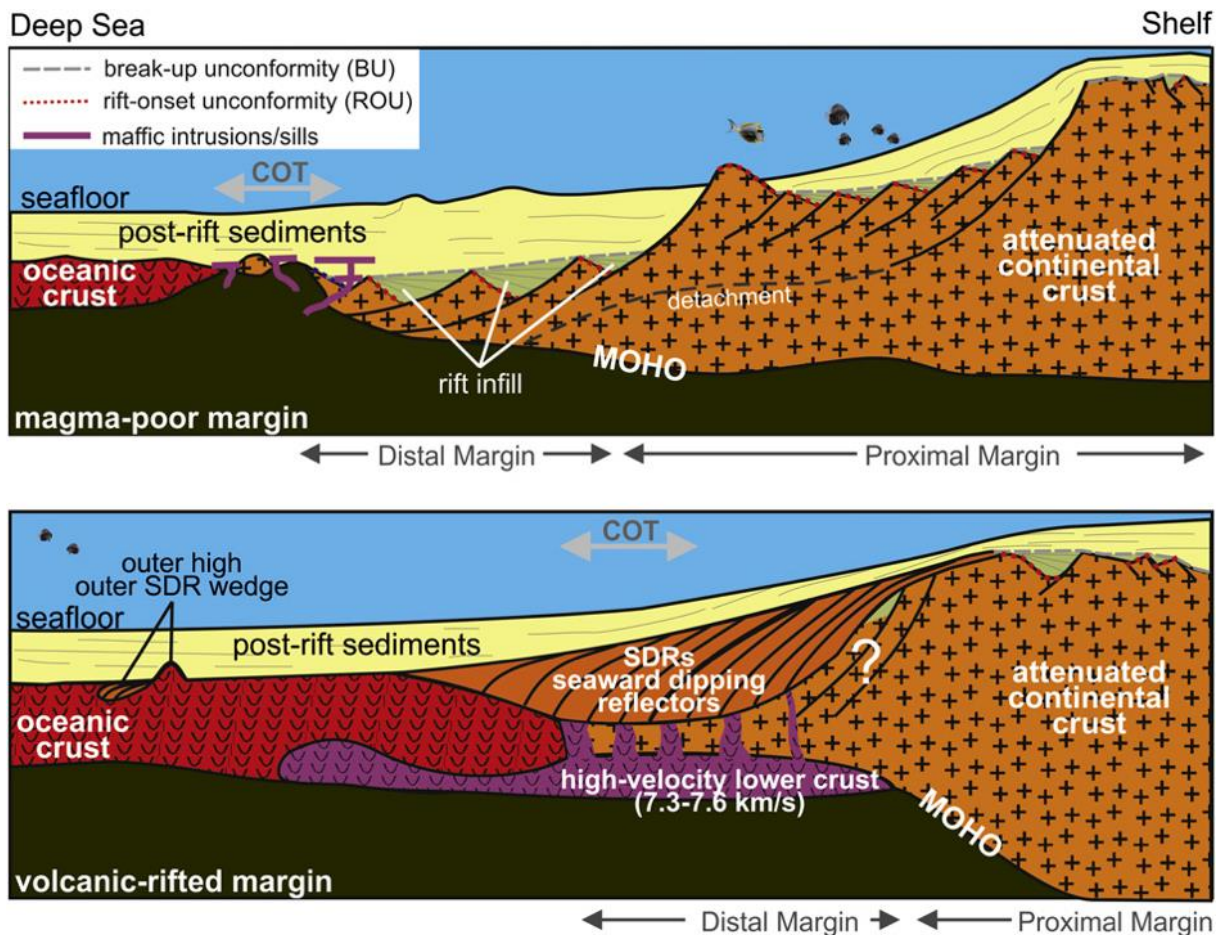


Figure 11: Comparison of magma-poor (top) and magma-rich (bottom) margins with first-order characteristics of reach margin (after Franke, 2013).

1.2.2. Building blocks of magma-rich rifted margins

SDR sequences

The main characteristic of magma-rich rifted margins is the succession of thick wedges of oceanward volcanic flows, referred to as SDRs (Sea Dipping Reflectors) for which two models of formation have been proposed (see Figure 12). The first one is a fault bounded model (Geoffroy, 2005), where wedging is due to the action of the landward dipping faults. This model has, however, been challenged as a landward dipping fault juxtaposing SDR sequences and oceanic crust would imply that the SDRs are post-breakup. Moreover, in many seismic sections SDR sequences cannot be observed, in particular in the most distal domains of magma-rich rifted margins (Buck, 2017). The second type of models explain the wedging solely by flexuring and loading of the magmatic flows toward the central magma source. These models ignore, however, that SDRs are bounded by faults, as observed in the more proximal parts of magma-rich rifted margins. As both models are still debated,

Harkin et al., (2019) suggested that one model does not exclude the other. In contrary, the authors explain the difference between inner and outer SDRs as linked to the process responsible of their creation. Inner SDRs downlap on continental crust in a subaerial context. (Geoffroy, 2001) noticed the syn-magmatic extension associated with crustal flexuring controlling the formation of the inner SDRs. These appear to be relatively sudden and to correspond to the necking domain of the magmatic margin (Geoffroy et al., 2015). Eldhom et al., (1989) demonstrated the subaerial setting of the inner SDRs by well data and log analyses of ODP Sites 642, 643, 918 along the Norwegian margin. These logs show the interbedding between lava flows of tholeiitic type magma and volcanoclastic sediments in the upper series and dacitic lava flows with thicker interbedded sediments in the lower series.

The outer SDR are emplaced in deeper environments where the flows spread above the axial magmatic source (Mutter et al., 1982; Quirk et al., 2014; Paton et al., 2017) and the observed wedge are due to flexure. The older SDR packages recede as the accretion of younger packages forms in the central part (see Figure 12b and also Buck, (2017)). The younger packages are supplied by several generation of dykes and sills (Geoffroy, 2005).

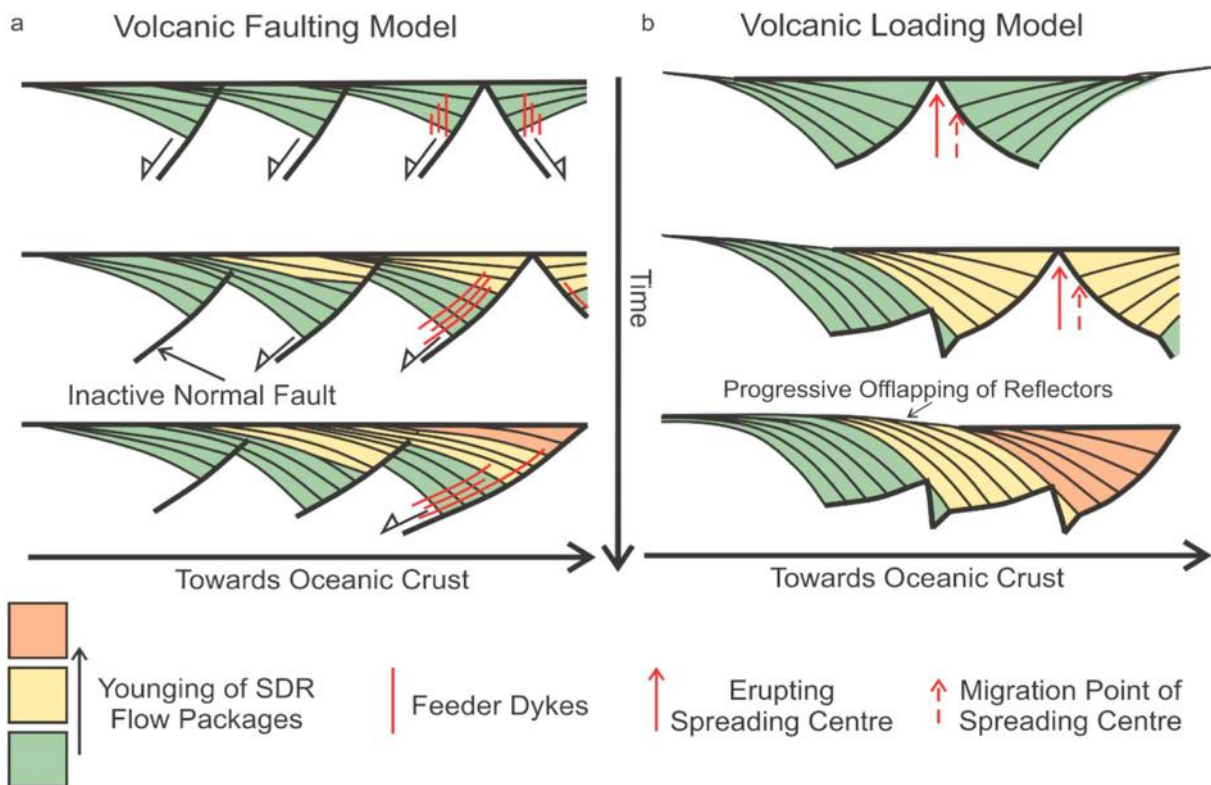


Figure 12: Evolutional sketch showing the two main models of emplacement of SDRs with syn-magmatism continentward dipping normal fault accommodating the wedges. Notice the different generation of dykes (from (Harkin et al., 2020)).

Many questions remain concerning the emplacement of the SDRs, the nature of the substratum, the real distinction between inner and outer SDRs, or the relation between magmatic and extensional processes, the volume of magmatic additions, which make that models of SDR formation are currently debated.

High velocity Lower Crustal bodies (LCB)

At magma-rich margins, high velocity bodies have been identified with P-wave velocity of about 7,3 km/s, which is significantly higher than the V_p of maximum 7km/s for a classical lower crust (Geoffroy, 2005; Mueller and Jokat, 2017) . At present, no drill hole penetrated such lower crustal bodies and there is no field analogue. Such bodies have been interpreted in the past as either massive intrusions into the lower crust, mafic underplating, serpentinized mantle, or high grade inherited metamorphic rocks (Franke, 2013; Nirrengarten et al., 2014). Gernigon et al., (2006) proposed that the LCB are inherited and form before the production of the SDR. In their interpretation, these bodies flooring the Vøring Margin are made of high-pressure rocks originating from the Caledonian orogeny. However, another interpretation is that these lower crustal bodies correspond to the “residual” part of the extrusive melting, in particular where such bodies are overlain by SDRs. Indeed, many petrological models attempt to estimate the ratio between extrusives (here, mainly SDRs) and intrusives (underplated magmatic material and intrusives in residual continental crust). In those studies, the estimations of this ratio are highly varying according to the tectonic settings, composition of magmas, but the lowest estimations consider an Extrusive to Intrusive ratio equal at least to 1:1 (Crisp, 1984; White et al., 2006).

Segmentation, symmetry and evolution of magma-rich rifted margins

The segmentation of magma-rich rifted margins has been interpreted to be related to the presence of a hot and weak magmatic centre, corresponding to the source of melting in the middle of a segment and feeding the related dyke swarm (Geoffroy, 2005, Figure 13). At the magmatic centre, the 1300°C isotherm raises up allowing melt production. Following Geoffroy (2005), the high-velocity LCB is thicker in the central part of the segment, as it represents the residual part of the melt body. Between two magmatic centres, the lithosphere is strong and thermally equilibrated. In Norcliffe et al., (2018), the authors notice the segmentation of the margin linked to onshore inherited structures. They also suggest a smaller scale segmentation as they observe a sequence of SDR that are laterally confined

(Laterally Confined Volcanic Sequence) in between sequences that are not segmented. These laterally confined sequence developed above laterally offset magmatic centres and this segmentation is overridden by a later rift jump.

The question to what extent conjugated magma-rich rifted margins can be symmetric or asymmetric has not been investigated in detail, although most of the models are proposing symmetric evolutions. Geoffroy et al., (2015), for instance show the evolution of a central block (C-block), which is progressively thinned by faults and simultaneous SDR development. However, the symmetry of the conjugated margins can be overwritten by rift jumps (see following section).

The transition to oceanic crust remains little understood. Eldholm et al. (1995) draw a continental dipping curved line, defining a discontinuity accommodating the emplacement of the last SDR. This transition could, however, be more gradual as observed in the Uruguayan margin (Clerc et al., 2015). Here the authors interpret ductile deformation in the lower crust controlling the thinning of the crust that is overprinted by magmatic additions that develop into a completely magmatic crust. Tugend et al., (2018) highlighted that interpreting the magmatic evolution of a rifted margin is non-unique and can result in several scenarios including sharp-fast or gradual-wide-slow breakups. This results in some key questions regarding the development of magma-rich margins and how far they are really related to a plume or a hot spot dynamic. Recent studies may show that rift propagation

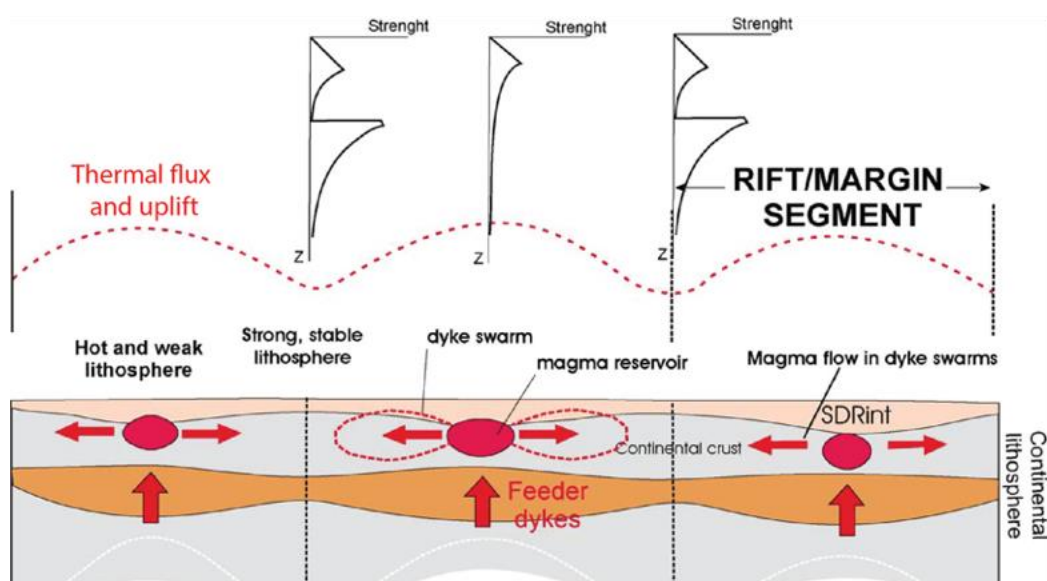


Figure 13: Segmentation of volcanic margins related to the position of hot and weak spot at the centre of the segment and strong lithosphere at the segment's end. (after, Geoffroy, 2005).

ignores the position of plume (Franke, 2013).

Rift Jump at magma-rich margins

At magma-rich margins, where the lithospheric break-up is supposed to be fast and where the magmatic and deformation processes are rapidly localising, it seems very unlikely to observe rift jump (Mutter et al., 1982; Quirk et al., 2014). However, relatively recent studies report evidence of rift jumps. Buck, (2017) presents a model based on the observation of unconformities in the SDR (Figure 14) in which the SDR sequences are formed by “out-of-sequence” and where the focus of the magmatic production jumps into a previous sequence of SDRs. In Norcliffe et al., (2018), the authors interpreted laterally confined volcanic sequence (segmented by transfer zones) and this segmentation is overprinted by a jump, which develop into a continuous SDR sequence.

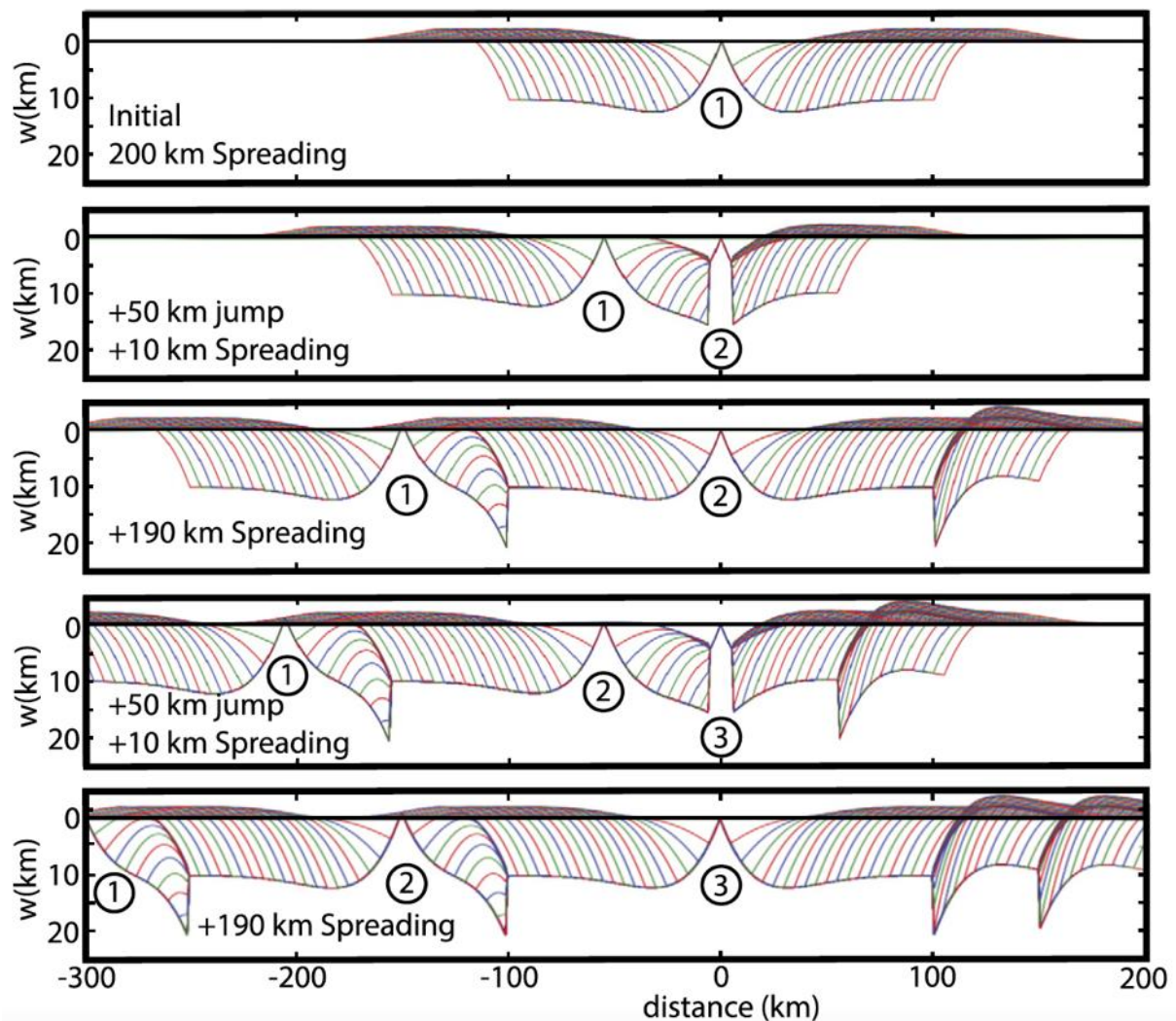


Figure 14: Modelling rift jump at magma rich margins with out-of-sequence SDR development (Buck et al., 2017). “w” is the vertical scale in kilometre.

1.3. Remaining questions

Major improvements have been made in understanding the evolution of magma-rich rifted margins. The first order architecture of these margins including the SDR sequences is well-studied. However, the nature of the crust underlying the SDR and its structure, and the relation between extrusive lava flows and the intrusive and underplates remain yet little constrained. Also, estimating the magmatic budget, especially the intrusive and/or underplating magmatism remains difficult to assess. The magmatic systems (from source, transport to emplacement) interactions with deformation are yet poorly understood, as we miss dynamic concepts that are not yet incorporated in the rifting models whereas they have major impact on the evolution rift systems. Finally, what is the nature of the transition to first oceanic crust and how and where the break-up is occurring, remains complex to understand.

2. The Mozambique Channel and Mozambique-Antarctica Conjugated margins

2.1. Why study the Mozambique-Antarctica conjugate margins?

The East African margin resulted from the complex, polyphase and segmented breakup of Gondwana. It comprises all extensive margin types, i.e. a magma-poor margin (e.g. Somalia) and a magma-rich margin (e.g. Mozambique), a transform margin (e.g. Tanzania) and an oblique margin (e.g. Kenya, Mozambique). The final architecture of these margins is controlled by the interplay of tectonic and magmatic processes and a complex inheritance that is the result of a long evolution, including several stages of the Wilson cycle responsible for a complex lithosphere and crust. This study will focus on the Mozambique Channel and the bounding conjugate margins, which are the Mozambique-Antarctica rifted margins (Figure 15). One main interest in studying these margins is that they are closely linked to the Karoo plume, which enables to answer to two first order questions, which are: 1) What is the relation between extensional (rifting) and magmatic processes at plume induced margins, and 2) How to restore plume-related extensional systems (tight fit reconstruction)? Moreover, from this margin we have access, through the collaboration with Total, to a large data set that serves as foundation for this study.

2.2. Geological setting

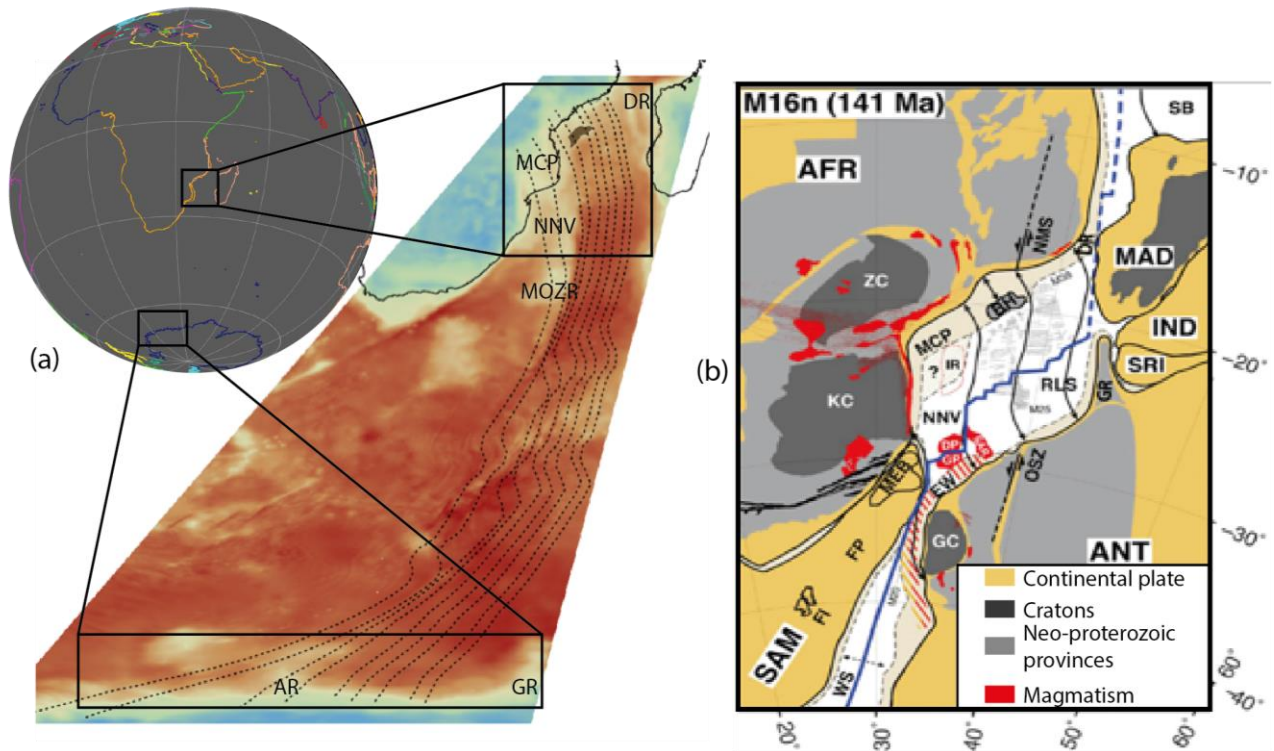


Figure 15: The Mozambique-Antarctica conjugated system. (a) Bathymetry map with the flowlines of Seton et al., 2012. (b) Reconstruction from (Schimschal and Jokat, 2019). AFR: Africa, ANT: Antarctica, IND: India, MAD: Madagascar, SAM: South America, SRI: Sri Lanka, DR: Davie Ridge, EW: Explora Wedge, FI: Falkland Islands, FP: Falkland Plateau, GC: Grunehogna Craton, GP: Galathea Plateau, GR: Gunnerus Ridge, IND: India, IR: Inharrime Ridge, KC: Kaapvaal Craton, MAD: Madagascar, MCP: Mozambique Coastal Plains, MEB: Maurice Ewing Bank, MozR: Mozambique Ridge, RLS: Riser Larsen Sea.

The lithosphere constituting the East African and Antarctica rifted margins represents a complex patchwork resulting from the stacking of events related to a long evolution spanning from the Archean to the Karoo. Most important events are the Panafrican Orogen, the Karoo Rifting and the final Gondwana Break-up. In the following, a short summary is presented with the aim to provide a first order overview of the inheritance of the margin and the main events pre-dating the rift evolution.

2.2.1. Pre-rift history

The pre - Pan-African history (Mesoproterozoic and Neoproterozoic evolution)

The formation of Rodinia resulted from major orogenic events that took place during the Meso- and Neoproterozoic (Li et al., 2008). This event is succeeded by the break-

up of Rodinia a process where continental rifting might have been associated with massive plumes (Cawood, 2005). The separation of Rodinia around 825Ma produced the continental fragments, which were amalgamated during the formation of the Gondwana continent.

The Pan-African Orogenic System and the amalgamation of Gondwana (Mesoproterozoic to early Cambrian)

The Pan African system corresponds to an orogenic system that resulted in the amalgamation the Gondwana super-continent at Neo-Proterozoic and early Cambrian time. Several geological provinces can be identified all along the East African margin. These provinces have been assembled along suture zones and collisional belts during the Neo-a

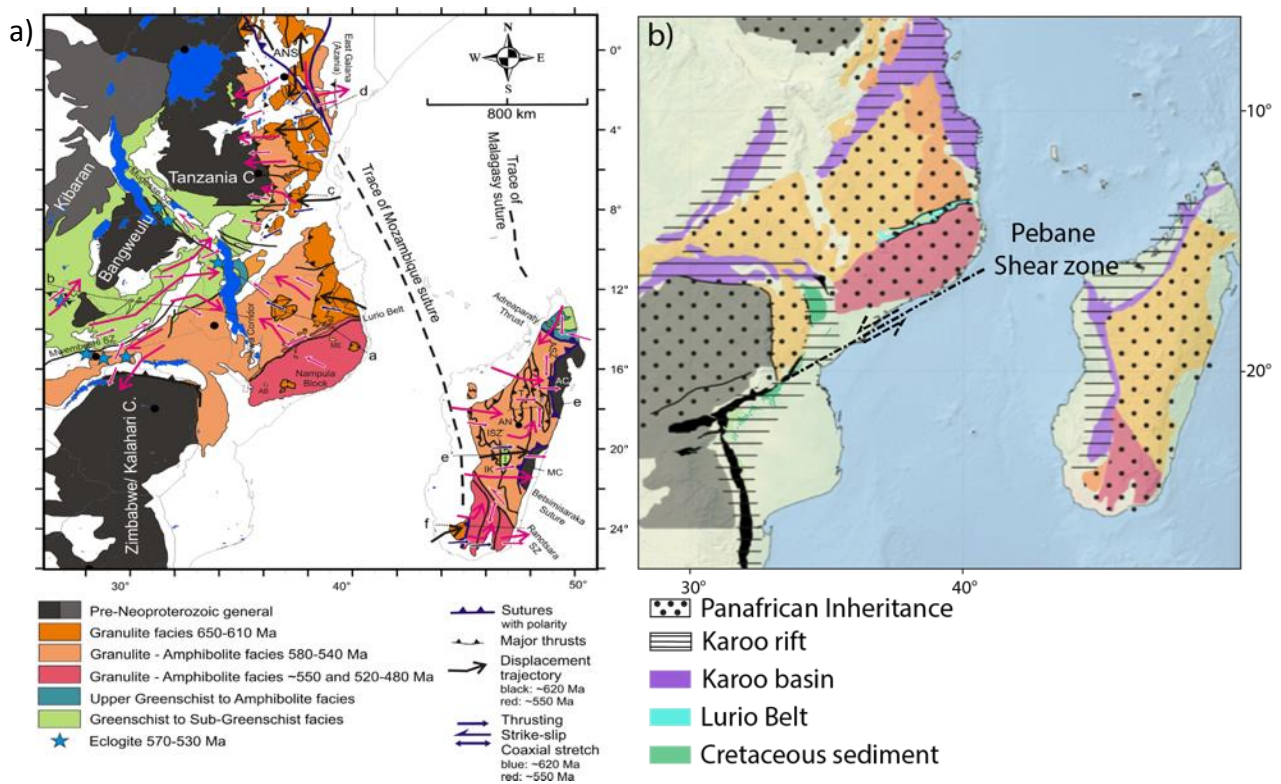


Figure 16: a) Geological provinces according to the distribution of petrological facies and their ages. Black arrows show the paleo displacement trajectory during the orogenic event. b) Different origins of inheritance. Dots region represents events linked to the Gondwana Amalgamation and the striped domain represents domains associated to the Karoo rift system (after Fritz et al., 2013).

The amalgamation of Gondwanaland ended around 530Ma leading to inherited structures presented in the following paragraph (Meert, 2003; Jacobs and Thomas, 2004; Li et al., 2008). According to (Fritz et al., 2013), this shear zone was active first in a transform motion during the late Neo-Proterozoic and then reactivated as extensional system. In the

northernmost part of Mozambique and in Tanzania, a long-thrust system dips to the NE extended to the south, bounded by the Lurio belt (Figure 16a). This thrust system accommodates the compressional deformation of two granulitic facies units at around 620 Ma.

The Lurio Belt is a suture zone separating the Unango Mapura complex to the north and the Nampula complex to the south. This belt endures a post collisional extension younger than 530Ma. Further west, The Zambezi Belt and the Schlesien-Mwembeshi Lineament in the continuity of the Lurio belt formed a 3000 km discontinuity corresponding to the suture of an embryonic oceanic basin in the Pan-African collisional event (Sacchi et al., 2000).

2.2.2. From the Karoo Rift system to final breakup

The Karoo rifting system

The formation of the Mozambique Channel is a consequence of the separation of Eastern Gondwana and include rifting and breakup between the Antarctica, Africa, and Madagascar plate. The inception of rifting is simultaneous with a wide-regional scale extrusive and intrusive volcanic activity described as the Karoo and Ferrar Igneous Provinces that are located along the proto southern Africa – Antarctica plates (Leinweber and Jokat, 2012; Hastie et al., 2014).

Two main orientations, one NW-SE and the other NE-SW can be observed in the rift system (Figure 16b and Figure 17, Wescott and Diggens, 1998; Delvaux, 2001; Catuneanu et al., 2005)). The Karoo rift system is believed to be a Permo-Triassic event that can be mapped across the Gondwana supercontinent. In the Mozambique Channel area this event is dated as an Early to Middle Jurassic extension phase. The Lebombo monocline marked by the NNW-SSE orientation of basaltic flows developed between 183 to 170Ma and may be linked to this event. Klausen, (2009) described these flows as eastward dipping SDRs. The authors revealed, based on field observations, that the tilting of the basaltic flows is coherent with a syn-extensional emplacement. They proposed that the flows close to the triple junction are related to plume activity and that the more distal flows are more tectonic related.

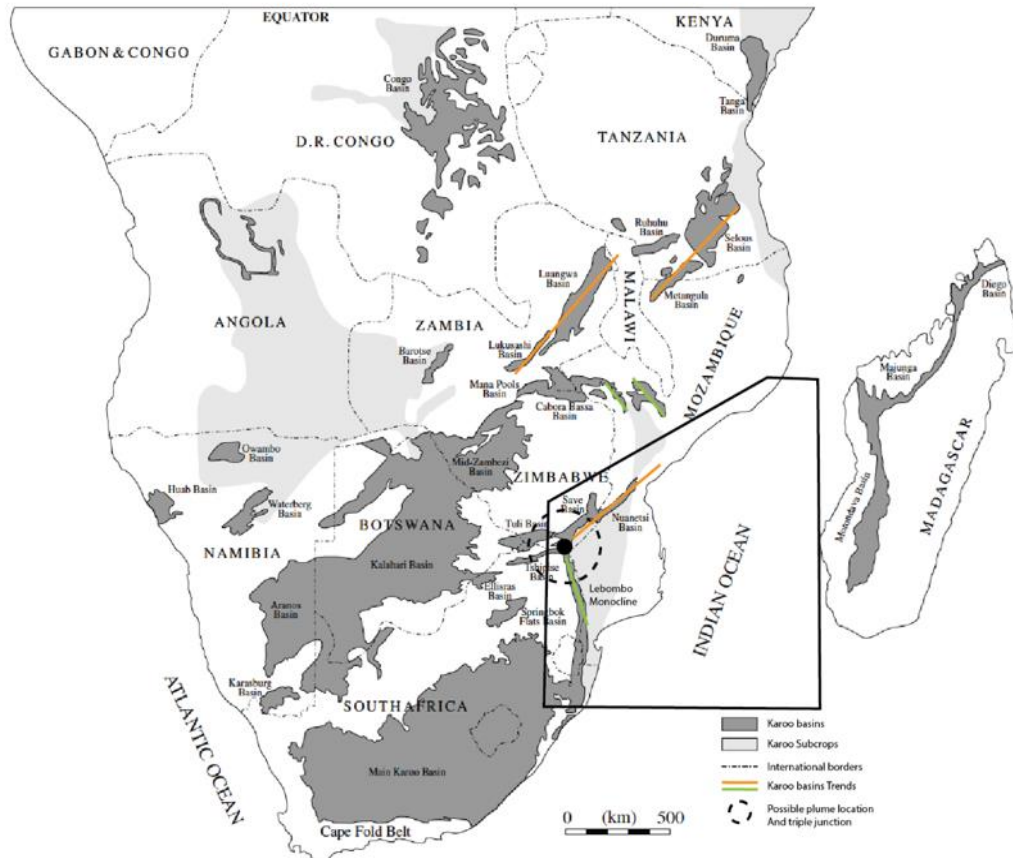


Figure 17: Karoo and Cenozoic rift depressions in southern East Africa. Notice the main NE-SW and NNW-SSE orientations of the rift (after Catuneanu et al., 2005; Johnson et al., 1996; Wescott and Diggins, 1998; Nyambe, 1999; Wopfner, 2002). Position of the triple junction and possible plume location is shown by black circles. Studied area is shown by black polygons.

Jurassic rifting and break-up

At present many rift models exist for the Mozambique Channel and main debates concern the nature of the crust flooring the Mozambique Coastal Plains and the Northern Natal Valley (Thompson et al., 2019, see Figure 18). Equally debated are the orientation of first extension, timing and change of kinematic direction as well as the timing of onset of magmatism and of seafloor spreading.

Concerning the initial movement of Antarctica relative to Africa, some models suggest an initial sinistral movement of Antarctica relative to Africa along the ENE-WSW Pebane shear zones (Cox, 1992; Senkans et al., 2019, Figure 16). However, most authors propose that the initial separation at 183Ma was directed NW–SE and then the oceanic crust spreading occurred after 60km to 80km of extension of the initial rift at 176Ma on the Angoche segment (Reeves and de Wit, 2000; Leinweber et al., 2013; Reeves et al., 2016;

Davis et al., 2016; Klimke et al., 2017). On the other hand, Nguyen et al. (2016) proposed an anticlockwise rotation of Antarctica as the first initial movement between 184 and 171Ma based on the landward prolongation of fracture zone showed in 3D gravity inversion.

In contrast (Davis et al., 2016) choose as the start of seafloor spreading magnetic anomaly M25n (153Ma) based on the study of (Leinweber and Jokat, 2012). Later, (Leinweber et al., 2013) proposed a break-up at 171Ma and a first spreading in a SSE direction. Reeves et al., (2016) proposed a break-up occurring at 170Ma. the author suggested that Africa underwent extension of 60–120 km, while the Antarctic crust was stretched by 105–180 km along the divergent margins. On the other hand, other studies considered the Mozambique Coastal Plain (MCP) to be made entirely of igneous crust and the Mozambique Ridge as a succession of volcanic plateaus thickening the oceanic crust (Leinweber and Jokat, 2012; Davis et al., 2016; Klimke et al., 2017). In contrary, Reeves and de Wit, (2000), Senkans et al., (2019), Moulin et al., (2019) considered the MCP as continental crust, extending far south along the western side of the Mozambique Ridge.

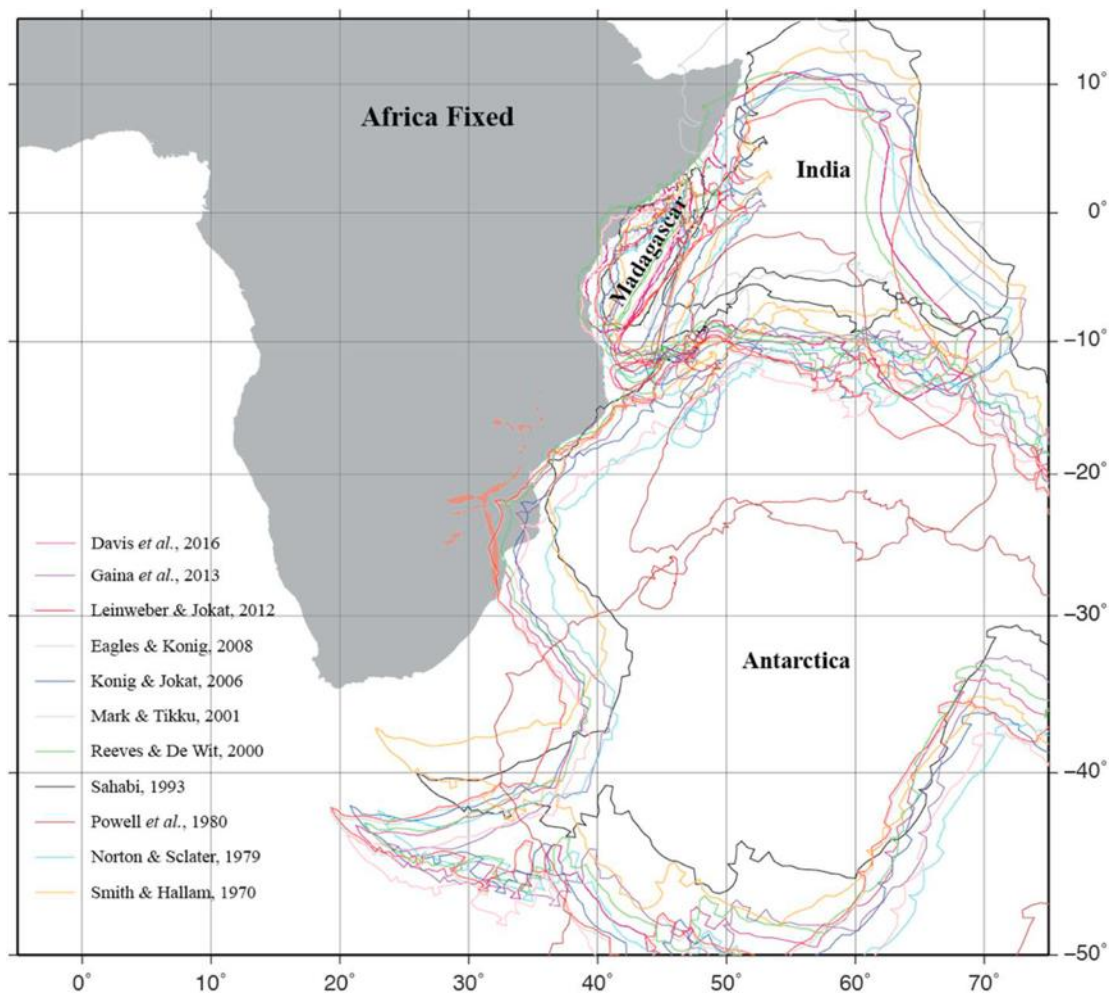


Figure 18: Compilation of initial fit from Thompson et al., 2019.

A consequence of the different kinematic interpretations and the debate of the nature of the crust flooring the MCP is that a number of different initial fit configurations exist for Mozambique Channel.

2.2.3. The Post-Breakup history

After lithospheric break-up, seafloor spreading started in a NW-SE direction as documented by Leinweber and Jokat, (2012), Leinweber et al., (2013), Davis et al., (2016).

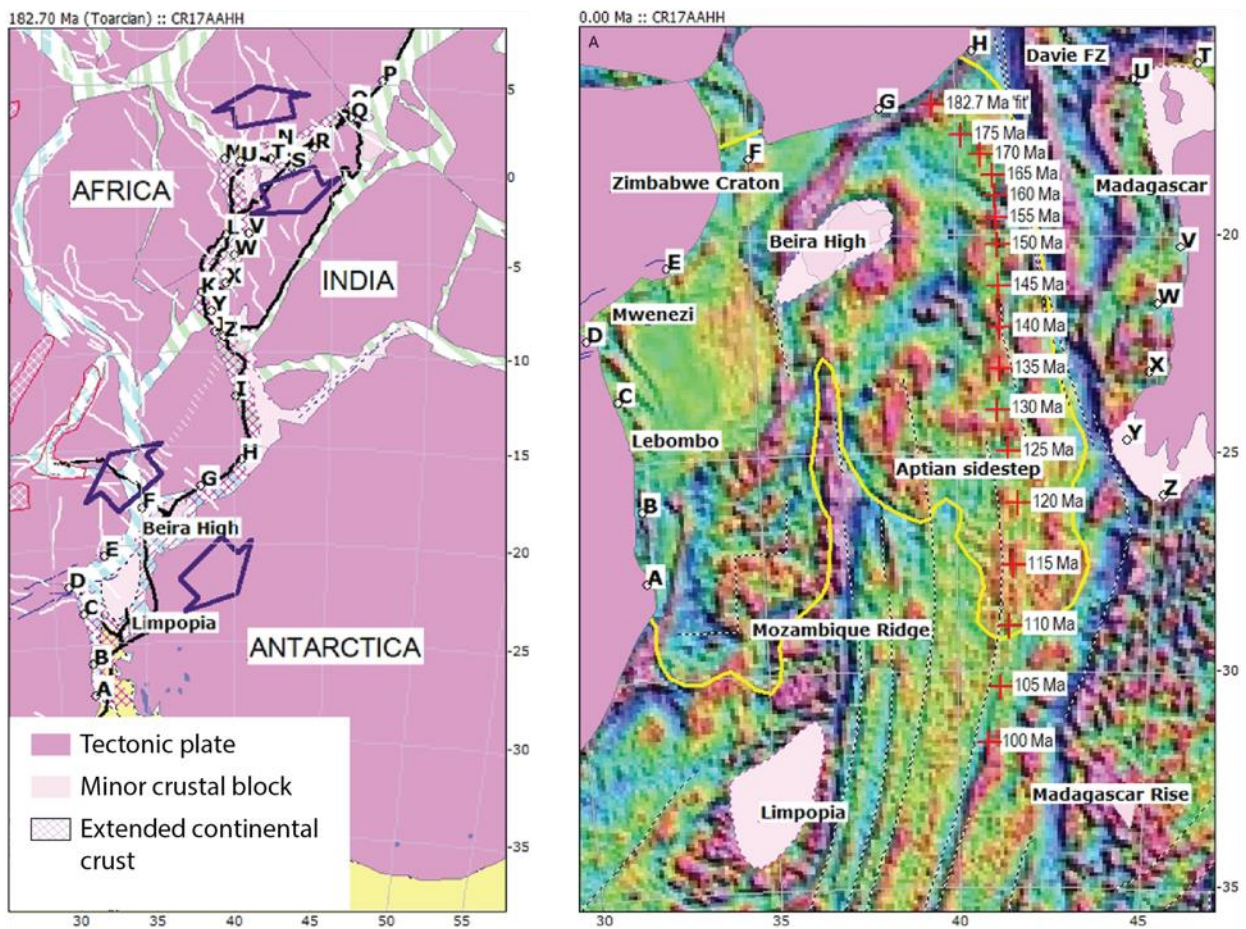


Figure 19: a) Initial movement of the separation of West and East Gondwana (183Ma), after Reeves, (2018). Notice the extension north of Limpopia and Beira High. White lines represent major gravity lineations. b) Actual state of the Mozambique basin with the position of the Beira High. Limpopia is as well a continental block and formed the southern Vauban plateau of the Mozambique Ridge (After Reeves, 2018).

Subsequently spreading first shifted to NNW-SSE direction around 167Ma (Reeves et al., 2016) before progressively moving in a N-S orientation at around 153Ma. As the spreading continued and Antarctica moving southward relative to Africa, the Mozambique Ridge formed. As some studies suggest that the Mozambique Ridge is thickens magmatic crust (König and Jokat, 2010; Fischer et al., 2017), others proposed that the southernmost

part of the Mozambique ridge is actually a Precambrian fragment (see in Reeves and de Wit, (2000), so-called “Limpopia“ fragment, (see Figure 19). This block stayed connected with Antarctica before the oceanic rift jump led to the separation of these blocks (Figure 19, Reeves et al., 2016). In this case, according to (Reeves, 2018), the margins of the Riser Larsen basin are considered as conjugate of the southern part of the Beira High and of the eastern or southern side of Limpopia (this statement is longer discuss in Chapter III).

The different models slightly diverge from each other by few degrees in orientation of the spreading, however these discrepancies are below the resolution and scope of this study that is mainly focused on the rifting and early seafloor spreading history the Mozambique channel.

2.3. Remaining debates

Even though the East African rifted margin in general and the Mozambique channel in particular have been intensely studied in the past, some major debates remain concerning the rifting history and the initial tight fit is still disputed. Thompson et al., 2019 compare some of the models and analyse the discrepancies and common characteristics of each model from initial fit to the end of spreading. The pre-break up kinematics are poorly constrained. A tighter fit than the fit proposed by Thompson et al., 2019 is possible and some of the main pin point are not respected by these authors. Major debates remain concerning the nature of the crust flooring the Mozambique Coastal Plains (MCP), the Northern Natal Valley (NNV) and the Beira High. Some authors proposed a magmatic crust in the MCP and NNV (Leinweber and Jokat, 2012; Davis et al., 2016; Klimke et al., 2017) while others suggested a continental inherited origin (Senkans et al., 2019; Thompson et al., 2019). On the Antarctica side, the conjugate margin is interpreted to be, based on gravity and seismic interpretations, the Riiser Larsen Sea bounded to its eastern side by the Gunnerus Ridge and to its western limit by the Astrid Ridge (Leitchenkov et al., 2008; Klimke et al., 2017). The location of the western boundary depends, however, on the nature of the Mozambique Coastal Plains.

3. Data & Method

3.1. Data

3.1.1. Seismic data

The data used in this study are mainly seismic data and include the MBWG13 survey acquired by Western Geco in 2013 with the M/V Pacific Falcon and M/V Western Patriot. A streamer of 10,3km length with an oblique depth from 8m to 35m has been used as a receiver. A 12s continuous recording was performed but only 10s lines were available in Total database. A state-of-the-art processing commonly used for this type of data (filtering, deconvolution, RMS velocities analysis, NMO, stack and migration) has been performed.

Along with this survey, on the Antarctica side, surveys for the German BGR96, BGR78 and ANT-VIII/6 cruise and the AWI61 survey and the Russian RAE surveys are used to describe the first order geometry of the genetic domains of the conjugate margins (for the whole dataset location see Figure 20).

3.1.2. Gravity Inversion

For the gravity inversion, we use public domain data including bathymetry (Amante and Eakins, 2009) and the satellite derived free air gravity anomalies data (Sandwell and Smith, 2009). Where possible, we used bathymetry and top basement interfaces from the dense industrial seismic dataset from Total. Finally, we performed a joint inversion on main interfaces from refraction data from the PAMELA project, especial MZ7 and MZ1 lines (Moulin et al., 2019) and also on refraction lines from Mueller and Jokat, (2017), (see chapter III for details).

3.2. Method

This study initiated with an 8 months long visit of the R&D in TOTAL in Pau, SW-France during which I gathered and revised previous interpretations of the region. During this stay, a large amount of data has been re-interpreted, rift domains have been mapped, wells have been analysed, and seismic data from Antarctica margin has been reloaded in the seismic project and interpreted and linked to the data of the conjugate margin. All over, more than one year of my PhD has been used to get access, interpret and map the complete data set.

During a second part, in Strasbourg, the analysis of the data and maps led to the conclusion that the existing data set will not allow to propose one, coherent interpretation.

The main problems were the lack of access to drill hole data to get more precise time constraints on the evolution of the distal margins. A second, but more important problem in the whole study area, was the masking of rift structures responsible for the crustal thinning by a thick and extensive magmatic system. Therefore, more than 18 months after the start of the PhD, we decided to develop a new strategy in order to answer to the key scientific questions addressed in this PhD. The strategy was based on working with different end-member scenarios and the use of different methodological approaches. Based on the large data set and interpretations acquired in the first half of the PhD, I proposed different end-member scenarios and used Gplates to analyse their limitations and propose a more realistic tight fit scenario (paper 1). The use of new and existing quantification methods, in collaboration with Nick Kusznir (University of Liverpool) enabled me to test some of the hypothesis (papers 1, 2, 3). Finally, the use of a “simple” tool to generate first order margin architectures enabled me to discuss the role of the magmatic budget and of the relative timing of onset of magma-production in controlling the first order crustal shape of rifted margins.

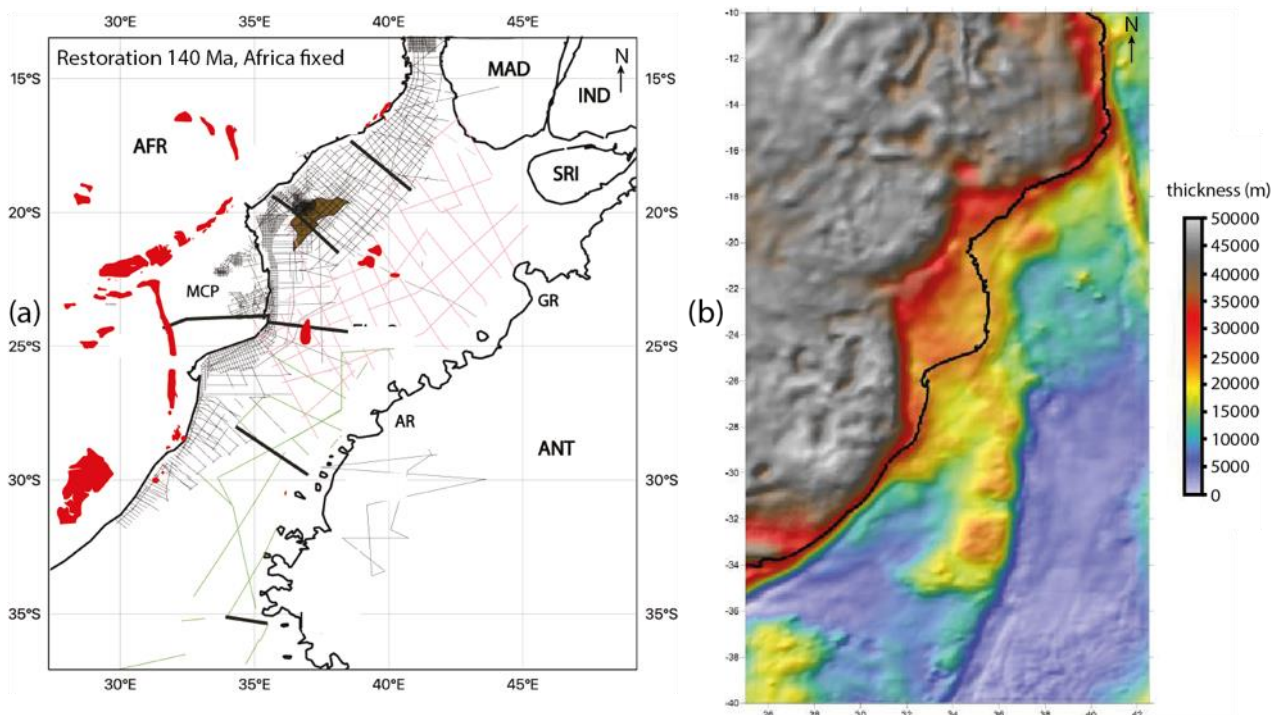


Figure 20: (a) Seismic 2D Dataset used to map rift domain in Mozambique and Antarctica. (b) Gravity inversion performed to obtain crustal thickness map of Mozambique after Chappell and Kusznir, 2008. Thick black lines represent the seismic data interpreted in Chapter II. In red is the magmatism from Mueller et al. (2017).

Concerning the gravity inversion, the methodology applied here is described in (Chappell and Kusznir, 2008) and (Barnett-Moore et al., 2018) and the work has been done in close interaction with Nick Kusznir. The gravity modelling focused on several objectives:

- 1) 3D gravity inversion at a basin scale enabled to enhance and visualize the margin structures and to differentiate between different genetics domains
- 2) 2D inversion methods focused on 2D lines to assess the possible presence of intrusions, the Moho depth, and the location of the Continent-Ocean Boundary

I also realized a subsidence analysis of the domain associated to plume thermal support with the aim to assess the importance of the thermal subsidence.

4. Key scientific questions addressed in the PhD

The study of magma-rich rifted margins has intensively improved in the last decade due to the ground-breaking access to new high-resolution seismic imaging of magmatic margins. The new data sets enable to image the whole crustal structure, and in particular also the SDR, the emblematic structures defining magmatic margins. Many recent papers have characterized and discussed the processes that may explain these structures, as well as the segmentation of these margins, the processes of melt production and many other aspects of magma-rich extensional systems. However, some first order points are still debated. The aim of this study is to characterize at first order plume related extensive systems.

In this study, I'm assessing how to restore margins with enormous magmatic additions (extrusive and intrusive) and, subsequently, how to find the initial fit of conjugated systems. Indeed, such systems may form a basement where the proportion of magmatic addition and continental crust is very difficult to evaluate (this type of crust is referred as hybrid crust in this study), resulting in the impossibility to restore properly the deformation. As a study case I used the Mozambique-Antarctica conjugated system, for which the kinematic restoration remains highly debated.

The second main issue concerns the characterization of hybrid crust. Imaging this kind of crust is technically complicated as magmatic material absorb most of the energy of seismic waves. Moreover, velocities and densities of igneous materials are non-unique and cannot be used to distinguish between inherited continental and new igneous crusts. Therefore, I test the combination of geophysical methods to characterize hybrid crust?

In the last part of my study I open to a more global and first order view of magma-rich margins by re-assessing the magma-poor/magma-rich classifications and asking what are the key parameters controlling the architecture of Atlantic type rifted margins.

5. Structure and content of the PhD

The aim of the first chapter of this Ph.D. is to establish the geological background of what I studied during my PhD. This includes a presentation of the state of the art of magma-rich rift systems, the geological setting of the study area and a presentation of the main data sets, methods and questions addressed in this study. The synthesis of magma-rich rifted margins tries to highlight what are the key points that are still poorly understood concerning their description and evolution. The geological setting of the Mozambique-Antarctica conjugate system focusses to the main events during its long geological history. An overview of the different data, methods and approaches as well as a concise summary of the main questions and actions taken to answer them during my PhD is finalizing this first chapter.

The second chapter is using the example of the Mozambique and Antarctica conjugated rifted margins to understand how to restore the tightest fit in plume related magma-rich rifted margins. The interpretation of a dense 2D seismic dataset is presented on a map showing three domains, two that are of unequivocal continental and oceanic origin and a third that is hybrid and can be a combination of continental and magmatic. This chapter is based on a manuscript ready to be submitted entitled: "The challenge in restoring magma-rich rifted margins: the example of the Mozambique-Antarctica conjugate margins".

The third chapter is investigating the "hybrid crust", discussed in the first chapter, by set of geophysical approaches to test the geological nature of the crust. It combines 3D gravity inversion using the 2D seismic reflexion dataset interpreted previously, gravity inversion using refraction data of first order geological interfaces which are Moho and top basement, and a subsidence analysis of the Mozambique Coastal Plains. This chapter consists of a paper in preparation for submission to a geophysical journal entitled: "Geophysical and geological analysis of "hybrid crust" in extremely magma-rich margins: the examples of the Mozambique Coastal Plains and Beira High".

The fourth chapter is re-evaluating the classical magma-rich vs. magma-poor margins by presenting two key parameters that are controlling the architecture of mono-phased margins: the magmatic budget and the relative timing to extension. Based on a simple tool a

panel of thermally equilibrated first order margin architectures are generated, discussed and compared with present-day shapes of margins. This manuscript, entitled: "A new approach to characterize margins: linking crustal shapes to magmatic timing and budget, is planned to be submitted to *Geology*.

The fifth chapter discusses the results an idea developed during the PhD and answers to the key questions listed in the first chapter. In an outlook, I conclude, by summarizing the main results of the Ph.D. and showing the consequences for the present-day understanding of magma-rich rifted margins. I discuss the limitations of my study and possible short-cut and what could/need to be addresses in further studies.

The appendix gathers part of the work that has not been described in the rest of the manuscript and which might be relevant to fully understand the approach presented in chapters two to four in the Ph.D.

The first chapter sets the state of the art of how magmatism occurs during the formation of rifting margin. Also, the study case has been introduced. Finally, the key questions which are the guidelines of this manuscript has been identified. The next chapter, I propose a new method to identify crustal nature and estimate magmatic budget when the seismic interpretation is hindered by magmatism.

Chapter II: The challenge in
restoring magma-rich rifted
margins: the example of the
Mozambique-Antarctica
conjugate margins

The challenge in restoring magma-rich rifted margins: the example of the Mozambique-Antarctica conjugate margins

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Abstract:

How continental lithosphere ruptures in the presence of a mantle plume or excess magmatic activity, and how magma interacts with extensional processes leading to breakup and steady state seafloor spreading is not well understood. The extensive magmatic additions formed in the presence of a plume during rifting mask the edges of the continental crust and make it difficult to determine a tight restoration of conjugate margins and their evolution prior to breakup. The aim of this study is twofold: 1) to present a geological approach to determine the initial fit of the conjugate Mozambique-Antarctica rifted margins which formed during the eruption of the Karoo plume, and 2) to better constrain when, where and how magma formed during the formation of these margins.

In this study, we describe southern Mozambique rifted margins, propose a new rift domain map and investigate different plate kinematic scenarios assuming different magmatic budgets. We discuss different breakup histories, plate restorations and their tightness of fit, and evaluate the volume of magmatic additions formed during breakup. We examine the complexity of restoring and understanding the evolution of such magmatic

systems and their link to extensional systems. Although this study cannot be definitive, we present our preferred evolution for the conjugate Mozambique-Antarctica rifted margins.

1. Introduction

Although the architecture of plume related rifted margins has been intensively studied (Geoffroy, 2005; Franke, 2013), unknowns remain concerning fundamental first order interpretations of such margins. The evolution of magma-rich rifted margins related to deep seated mantle plume processes and the way they interact with extension and control the evolution and final breakup of rifted margins is not well understood (Tugend et al., 2018). Determining the nature and relative volumes of magmatic vs. original crust in the domain between unequivocal oceanic and continental crusts is difficult but necessary to propose tight fit restorations. The aim of this study is to better constrain the initial fit prior to the breakup of Africa and Antarctica and to determine the role and volume of magma formed prior to, during and after breakup at the conjugate Mozambique-Antarctica rifted margins. Recent studies have described the kinematic evolution of the East African margin by analysing the magnetic anomalies and seafloor fabrics (e.g. Reeves et al., 2013; Davis et al., 2016, (Leinweber and Jokat, 2012)) or by the interpretation of 2D seismic lines (e.g. Klimke et al., 2016). However, the nature and composition of key areas (e.g. Mozambique Coastal plains, Davison and Steel, 2018, Figure 21a), remain unconstrained and have a major implications on the determination of the timing and volume of magmatism formed from the Karoo-Ferrar Bouvet Plume and break-up processes.

In this study we propose a new rift domain map based on the interpretation of seismic lines in the Mozambique and the Riiser-Larsen Sea basins and gravity inversion to determine Moho depth and crustal basement thickness. We investigate different plate kinematic scenarii with variable budgets of magma showing different rift and breakup histories and different implications for the tightness of conjugate margin reconstructions. Although the available data allow us to propose a most likely scenario, we attempt to constrain the limitations of different interpretations and to discuss their consequences and implications.

2. Geological setting

The Mozambique and the conjugate Riiser-Larsen Sea margins offshore Antarctica are the result of the Gondwana dispersal that occurred about 180My ago. In order to restore

the Gondwana supercontinent, Thompson et al., (2019) presented a break-up fit between India, Africa and Antarctica highlighting the presence of Neo-Proterozoic Panafrican orogenic structures (e.g. Mozambique belt, Madra suture in Somalia) along with well-defined geological provinces (e.g. Nampula province in Northern Mozambique, Vijayan block in Sri Lanka, Kalahari craton in South Africa, Grunehogna Craton in Antarctica) that can be used as pin-points or alignments constraining the restoration (Fritz et al., 2013; Hargrove et al., 2003; Davis et al., 2016). However, very few models have presented the original tight fit restoration prior to break-up (e.g. Nguyen et al., 2016), and none of them discuss the importance of the magmatic budget in restoring the tight fit.

The initiation of the separation of Gondwana and, thus, the opening of the Mozambique Basin is commonly associated with the climax of the Karoo-Ferrar Large Igneous Province forming between 184-170Ma and spreading across southern Africa and Antarctica (Mueller and Jokat, 2019, Figure 21a). Late Jurassic rift basins related to this evolution present two structural trends, one that is NNW-SSE and the other which is NE-SW (Delvaux, 2001).

Many models, based on magnetic anomalies and seafloor fabrics (Leinweber and Jokat, 2012; Mahanjane, 2012; Davis et al., 2016; Reeves, 2018), present discrepancies in the spreading direction in particular during the initial stages of breakup. Cox, 1992 and Senkans et al., 2019, proposed an early ENE-WSW extension, while Reeves, 2000, proposed a NW-SE extension at about 180Ma. More recently, a study from (Leinweber and Jokat, 2012) described older magnetic anomalies M33n and even M41n (Leinweber et al., 2013). The first spreading has been assumed to occur prior to M33n with a shift to N-S spreading around 163Ma.

Klimke et al., 2017 interpreted similar structural patterns in the basement at the foot of the continental slope on the Mozambique side close to the Davie Ridge as well as on the Gunnerus Ridge, concluding that these two ridges are conjugates. This defines the eastern limitation of the studied domain.

The main uncertainty remains the nature of the Beira High and the Mozambique Coastal Plain (Leinweber et al., 2013; Mueller et al., 2016). The nature of the crust for both is still debated but crucial for the interpretation of the evolution of lithospheric breakup. An important feature is the Lebombo monocline, described as SDRs by (Klausen, 2009). The nature of the basement flooring the Mozambique Coastal Plains remains debateable. From

seismic interpretation and from wells, Davison and Steel, 2018 summarised the stratigraphic sequence in the Mozambique Coastal Plains, identified N-S trending Cretaceous basins and a magmatic top basement. A key question addressed in this study is the nature of the crust flooring the Mozambique Coastal Plains.

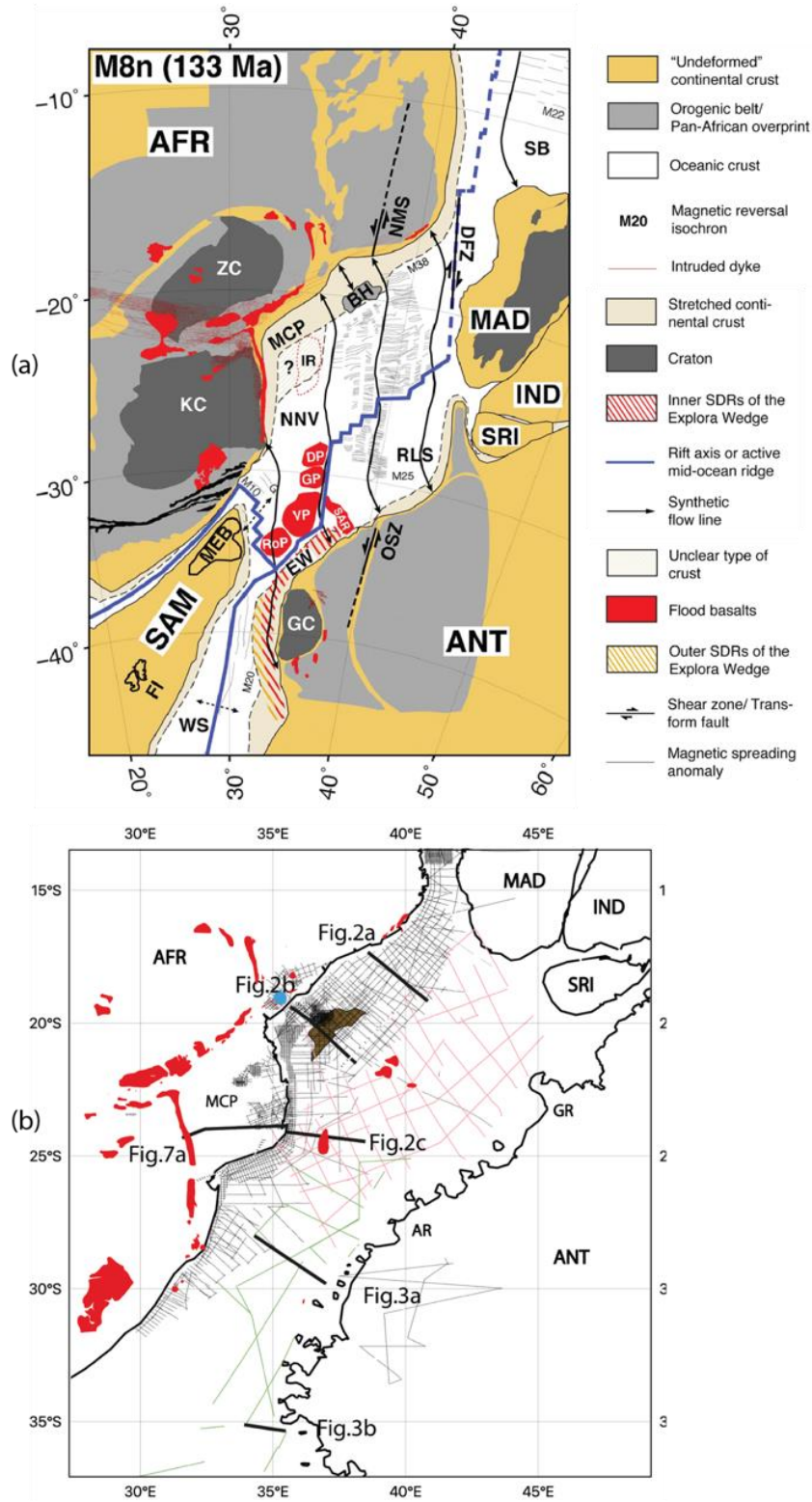


Figure 21: a) Simplified restored map of main geological provinces showing main boundaries, magmatic events (in red) and cratons that are represented in dark grey. Possible pin points used for the tight fit reconstruction are shown (e.g. Cratons: GC/KC, structures: NMS/OSZ, GR/DR); modified after Mueller et al., 2019. DR, Davie Ridge, EW: Explora Wedge, FI: Falkland Islands, FP: Falkland Plateau, GC: Grunehogna Craton, GP: Galathea Plateau, GR: Gunnerus Ridge, IND: India, IR: Inharrime Ridge, KC: Kaapvaal Craton, MAD: Madagascar, MCP: Mozambique Coastal Plains, MEB: Maurice Ewing Bank, MozR: Mozambique Ridge, RLS: Riser Larsen Sea). b) Set of seismic reflection data of the Mozambique Basin. In red RAE Russian dataset, in green, BGR dataset and in black the Mozambique Datasets from industry used to map the rift domains shown in Figure 24. Bold black lines are presented in this study (Figure 22 and Figure 23). Location of Nhamura well is shown by the blue circle.

3. Method and database

In this study we use a seismic survey from WesternGeco, shot in 2013 along the whole Mozambique margin to interpret the nature and structure of the margin. The dataset has been acquired by a slanted-streamer broadband acquisition with a long-offset 10km streamer. The migration performed is an anisotropic Kirchhoff prestack time migration. Additional surveys have been used to complete missing information. The Mozambique data interpreted in this study were imaged down to 10s-Two-Way-Travel-Time (TWTT). The stratigraphic ages are calibrated up to Neocomian from the onshore Nhamura well (see Figure 21b).

On the Antarctica side, seismic lines from the German BGR78, BGR96, ANT-VIII/6 and the AWI61 surveys and the Russian RAE surveys are used to describe a first order geometry of the genetic domains of the conjugate margins. No age calibration from wells are available.

Grids of crustal thickness for the Mozambique margin, its Antarctic conjugate and oceanic region in between were provided by Badleys Geosciences and were extracted from the global mapping reported in Kuszniir et al. (2018) and Alvey et al. (2018a&b). The crustal thickness mapping uses gravity inversion incorporating a lithosphere thermal gravity anomaly correction for oceanic and rifted margin lithosphere. The methodology and assumptions have been described elsewhere (Chappell & Kuszniir 2008, Alvey et al. 2008). Input data is satellite derived free air gravity anomaly, bathymetry and sediment thickness. The gravity inversion is carried out in the 3D spectral domain to produce 3D Moho depth, crustal basement thickness and lithosphere thinning factor. Ocean isochrons (Mueller et al. 2018) and rifted margin breakup age are used to determine the cooling ages for thermal re-equilibration of oceanic and continental margin lithosphere and hence their present-day thermal anomaly and lithosphere thermal gravity anomaly. We use the crustal thickness mapping in plate restorations to determine overlap due to excess magmatism. We also extract 9 profiles from the crustal thickness grid along sea-floor spreading flow-lines from the Mozambique margin to its Antarctic conjugate. We integrate crustal thickness along these profiles for comparison along strike and with that expected for normal, Penrose oceanic crust. Areas of abnormal crustal thickness can correspond to either thick oceanic crust or thinned original continental crust over and underlain by magmatic additions.

4. Results

4.1. Mozambique margin

4.1.1. Nature of the crust and distribution of rift domains

The systematic interpretation of the dense seismic dataset highlights two clear crustal boundaries. The first boundary delimits the unequivocal continental domain made of inherited crustal basement from new magmatic dominated basement. The inboard domain of this limit is made of basement that is little affected by Mesozoic extension, has a thickness of 30km or more and no or little accommodation space. As a consequence, these areas are sub-areal or in shelf settings, have non or very thin syn- and post rift sediments. Karoo related magmatic additions occur, but the overall inherited nature of the basement is well constrained. This boundary marks the undisputable limit of the inherited continental crust that cannot be overlapped in tight fit restorations.

The second major boundary is the landward limit of first unequivocal Penrose type oceanic crust. Outboard of this limit, the oceanic crust is a normal, about 7km thick crust showing well defined oceanic magnetic lineation. The steady state oceanic crust is also marked by sub horizontal top basement (at about 7s TWTT) and shows a passive infill of the overlying sediments. Moho is scarcely present, mainly due to limited imaging at depth (10sec TWTT data). Overall it appears that oceanic crust is normal to rather thicker than normal oceanic crust. Gravity analysis, suggest that the oceanic crust is thick (more than 10km) over 300km oceanward from the first magnetic anomaly (M31n) in the Mozambique Basin (see Figure 26a).

Between the two boundaries (for the position of the two boundaries see map in Figure 24), the crust is little structured and the most characteristic structural features are Seaward Dipping Reflectors (SDR) consisting of high amplitude reflectors. We consider SDR as a geometrical definition, however we assume that the reflectors are mainly volcanic flows that may form several units according to their dip and the migration of the pivot point/line. We are not able to define neither the volume of magmatic addition, nor the paleo-bathymetry at the time of their formation, nor the nature of the underlying basement in the reflection seismic data. The transition to unequivocal oceanic crust is defined by multiple top basement reflectors interpreted as volcanic flows, highly magmatic and possibly structured basement, and thicker than steady state Penrose oceanic crust.

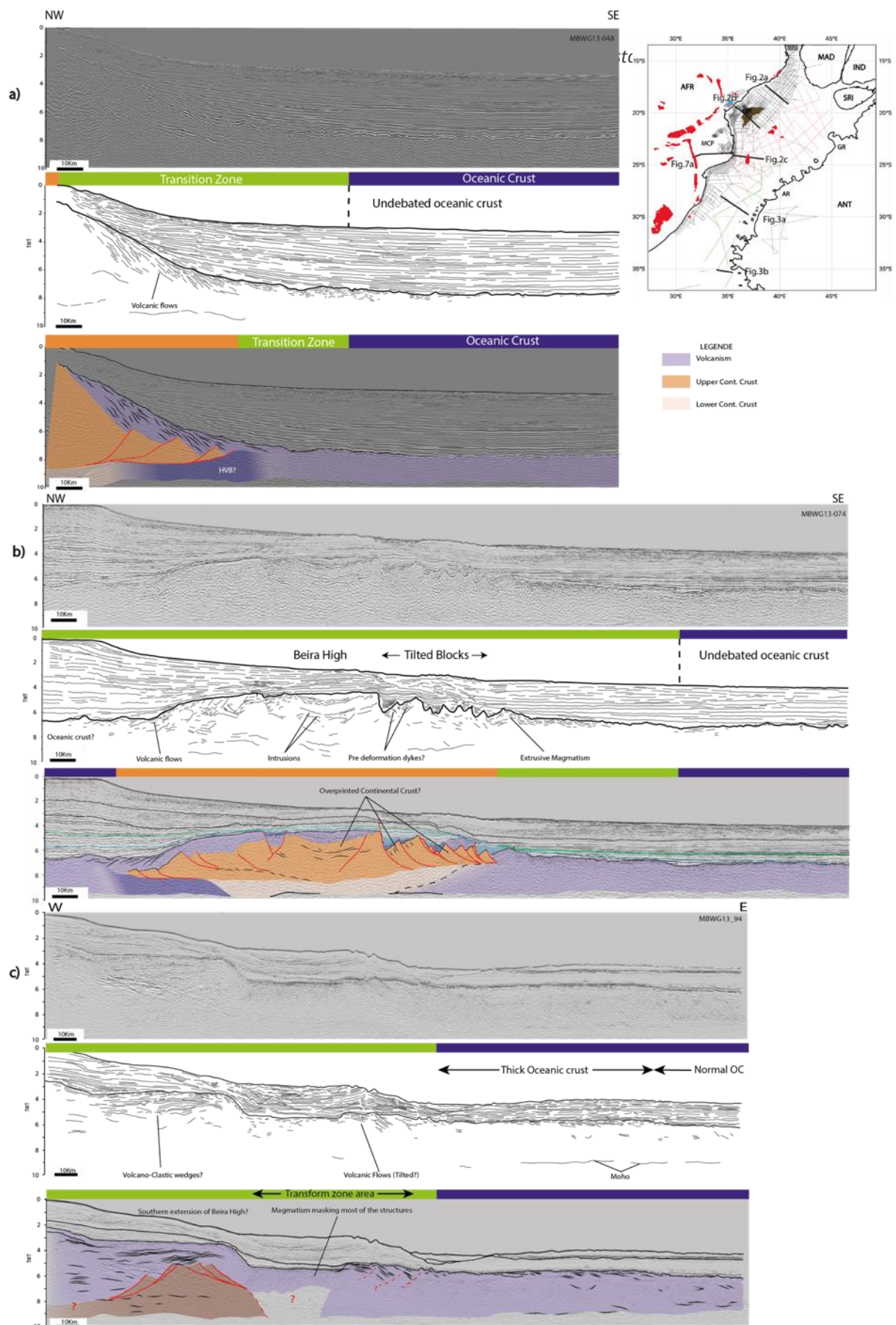


Figure 22: Three seismic lines showing aspects of each of the three identified Mozambique margin segments. Each line is displayed as black (top section), as a line drawing and as interpreted. The interpreted distribution of continental and magmatic crust corresponds to the resulting from the scenario analysis (see discussion of this chapter). Although clear oceanic crust is well identified in all sections, the nature of transition zone (green bar) can be debated. The ration between inherited continental crustal and magmatic material are chosen based on the tight fit scenario discussion (see discussion). For location of lines see Figure 21.

Locally, large offset listric faults (kilometre scale) can be observed affecting the basement and bounding syn-tectonic sedimentary packages with wedging type geometries (see Figure 22b). The nature of the crust, i.e. continental or magmatic, has major implications on the tight fit restoration of the margins. The observed faults affect a smooth top basement, but the fault heaves cannot explain the thickness of the underlying crust of the Beira High, which is about 25km. Throughout the whole area no evidence for mantle or lower crustal exhumation can be observed and top basement is little structured and masked by magmatic additions.

4.1.2. Segmentation of the margin

Mapping of the two major boundaries separating the unequivocal oceanward edge of continental crust and the continentward edge of oceanic crust, as well as of the main structures in the oceanic crust (magnetic anomalies and transform systems) enable to define ENE-WSW trending margins limited by NNW-SSE transform systems, resulting in strongly segmented margins. We propose to subdivide the Mozambique margin into three segments (see Figure 24) which are:

- 1) A divergent margin segment from the DFZ to the transfer zone east of the BH. A dip section across this segment is shown in (Figure 22a). The Continental Crust (C.C) is intruded and >25km thick. The crust is thinned progressively but the nature of top basement is clearly magmatic and the transition to steady state Oceanic Crust (OC) is characterised by a smooth top basement and a down-stepping onto oceanic crust.
- 2) A complex divergent margin segment with a structural high, bounded by two NW-SE transfer zones east and west of the BH. These transfer zones are marked by high magmatic activity and low offset extensional faulting. The segment is made of a proximal domain as shown in Mueller et al., 2017 based on refraction data. To the south, the Zambezi depression is floored by convergent sequences of SDRs with opposed polarities suggesting a failed rift (our interpretation; see also Mahanjane, 2012) (Figure 22b). The northern limit of the Beira High is made of well-developed SDR sequences. The basement in the central portion of the BH is 20 to 25Km thick according to refraction seismic data (Mueller and Jokat, 2017). The southern BH limit is affected by listric faults dipping toward the SE (Figure 2b). The basement is highly intruded by multiple magmatic events. Dykes prior to deformation may be interpreted as they are tilted by the faults and underlie syn-tectonic sequences. High-amplitude, irregular reflectors in the basement and in the sediments may

correspond to magmatic intrusions. At the transition towards OC no evidence for mantle or crustal exhumation can be seen and the nature of the transition is structured by magmatic material (Figure 22b).

3) A transform margin segment, with, however, bounding structures that are ill defined, due to the fact that the nature of the basement flooring the off and onshore Mozambique Coastal Plains remains debated (Figure 22c). Offshore, the Mozambique Coastal basement facies are similar to those flooring the BH and basement is 6s (TWTT) thick. Eastward of the basement high an abrupt thinning of the crust can be observed limited by thick oceanic crust. Westward of the basement high, thinning of the crust is more gradual and a sedimentary wedge thickening toward the west can be observed and capped by an erosional surface. The nature of the basement onshore of the Mozambique Coastal Plains is unconstrained, but the top of the crust is magmatic (Davison and Steel, 2018).

4.2. Conjugate Antarctica margin

The Davie Ridge and the Gunnerus Ridge mark the eastern limit of the segmented Riser Larsen Sea margin. The proximal part of the margin (more than 6s TWT thick crust) is only imaged on few seismic lines. The eastern part of the margin is assumedly poorly deformed as faults are rare and not well identified in the sections, although they might be masked by magmatic additions (see also Leitchenkov et al., 2008; Klimke et al., 2017). The margin is narrow with a short transition to unambiguous Penrose oceanic crust. The steady state oceanic crust is well imaged with a top oceanic crust averaging 8.5s n TWT. Moho is never visible which might be due to the fact that imaging stops at 10s TWT.

The second segment, close to the Astrid ridge, is much more complex: although the topography of the top basement is rough, the structures and magmatic additions responsible for the formation of the crust are difficult to determine. Neither clear faulting, nor sedimentary wedges or SDRs can be recognized. The transition domain from proximal to oceanic crust widens from about 20km close to the Astrid ridge to more than 150km north of the Astrid Ridge (from 20km wide to more than 150km, see Figure 21a). West of the Astrid ridge, SDR like geometries are very well recognized and a thick magmatic plateau can be observed (see Figure 23b). The magmatic budget appears to increase westward. This westward increase is also supported by the development of the Explora wedge that could indicate the direction toward the magmatic source that may be related to the Karoo-Ferrar

Plume. The clear limit of identified oceanic crust is shown on Figure 24. The most western part is characterized by an abrupt escarpment, where SDR developed downhill of the escarpment (Figure 23b).

Thus, like the northern conjugate margin, the Antarctica margin can also be subdivided into three segments.

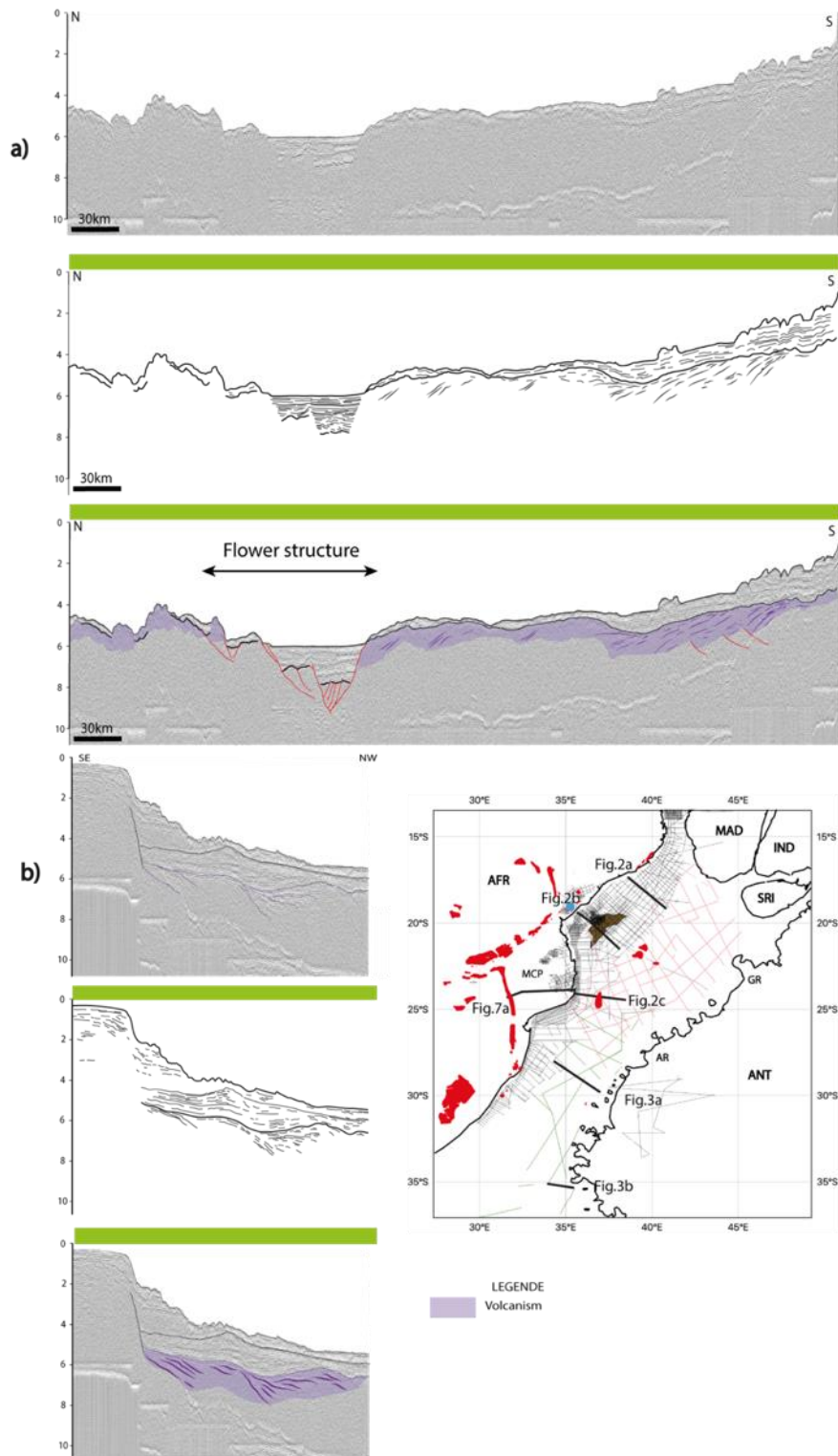


Figure 23: Interpretation of seismic lines of the Antarctica margins. Across the whole margin magmatism is present and tends to decrease eastward (see location Figure 21). a) Flower-shaped structure is assumed to correspond to the prolongation of the Andrew Bain fracture zone. b) Magmatic wedges (SDRs) imaged in the Explora wedge.

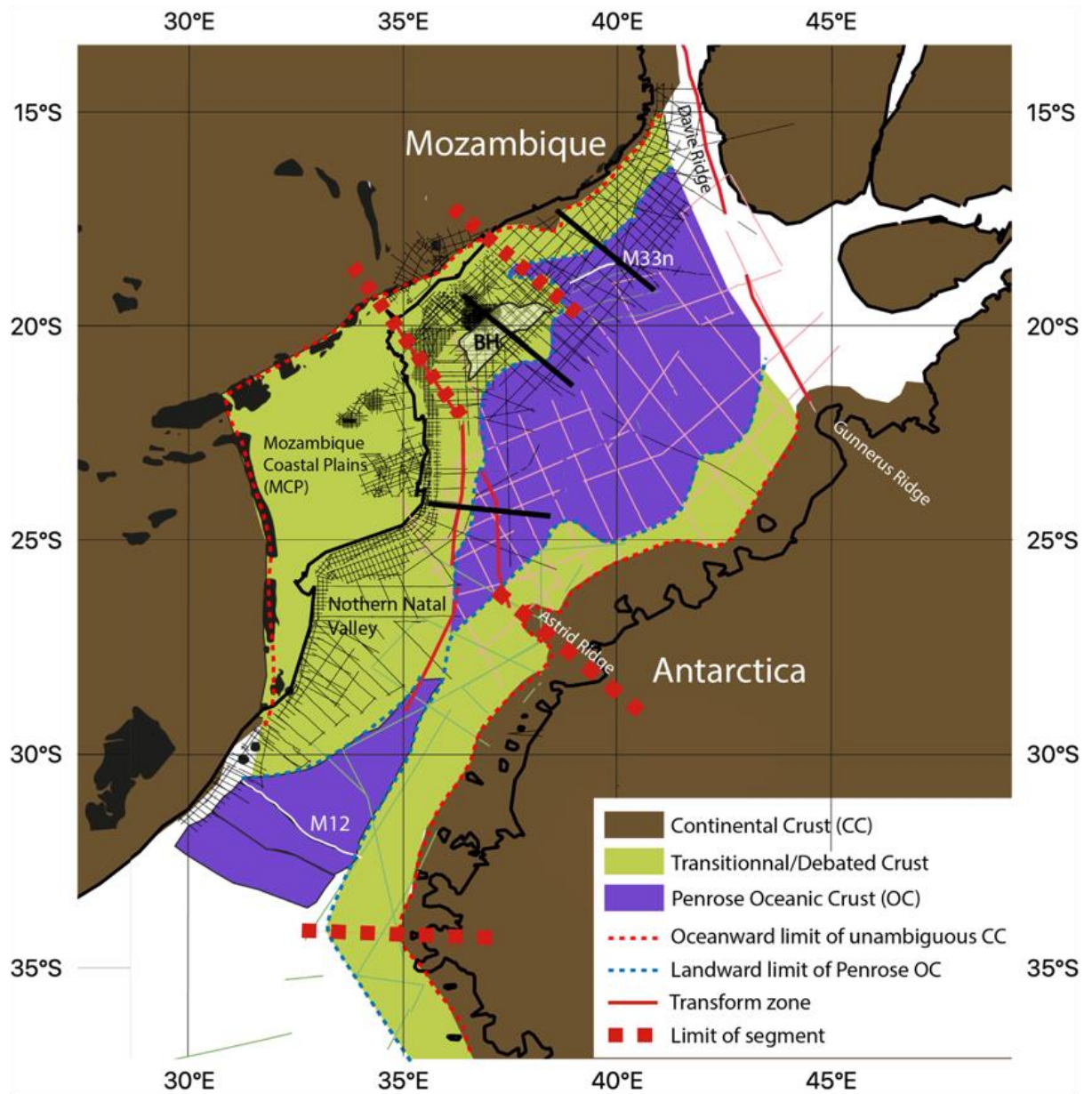


Figure 24: Map, restored at M16n (using poles of Davis et al., 2016), resulting from the seismic interpretation combined with geological evidence of volcanic activity highlighting 3 clear domains. The green domain represents de frame of freedom for the 3 scenarii testing.

5. Scenarii

In this section, the general approach consists in testing 3 scenarii where the transitional/debated crust (green area) is either entirely magmatic or entirely continental and the third scenario test a different early kinematic. We assess the restoration of each scenarii in regards to the different pin points and show the generated overlaps and gaps. This aim to provide a compromised

5.1. Approach

The philosophy behind the approach of this study is inspired from (Tugend et al., 2018). The authors demonstrate that the interpretation of the Ocean-Continent-Transition varies in terms of the magmatic budget and nature of the crust. Therefore, we take into consideration that the volume and timing of magmatic additions are difficult to determine unambiguously from seismic data. As discussed later, the interpretation of magmatic additions (budget and timing) has a major impact on the position of the oceanward termination of continental crust and how much can be restored in kinematic restorations to get the tightest fit. Nirrengarten et al., 2018 proposed a method to obtain a tighter initial fit by restoring the continental crustal section across rifted margins back to its original, pre-rift thickness. Their study dealt, however, with the magma-poor southern North Atlantic margins. In this study we want to extend the approach proposed by Nirrengarten et al. 2018 to magma-rich margins that rifted in the presence of a mantle plume and we restore the conjugated system considering palinspastic restoration.

We analysed previous models in order to identify similarities and differences among them. In addition, we used the constraints resulting from the seismic interpretation from the domains outboard of the limits of unequivocal continental and oceanic crusts along the conjugate margins (the brown and violet domains in Figure 24) and the kinematics defined for oceanic crust, which are altogether well constrained. For the green domain in (Figure 24), however, nature of crust and relative volume of new magmatic and pre-existing continental crust cannot be determined as well as the kinematics during its formation.

We test three different magmatic and kinematic scenarii for the formation of the green domain. Each of these scenarii have different magmatic budgets and kinematics for

the pre-breakup evolution of rifting along both conjugate margins. Our approach proposes and analyses end-member tight fit scenarii in terms of magmatic budget and kinematics. This first order, simple approach enables us to test the importance of magmatic additions and to estimate their volume in the analysed sections in different tight fit restorations. We use G-plates (Müller et al., 2018) to restore the margins. We then discuss the different scenarii to highlight consequences, which enables us to re-analyse the transition domain for the preferred scenario.

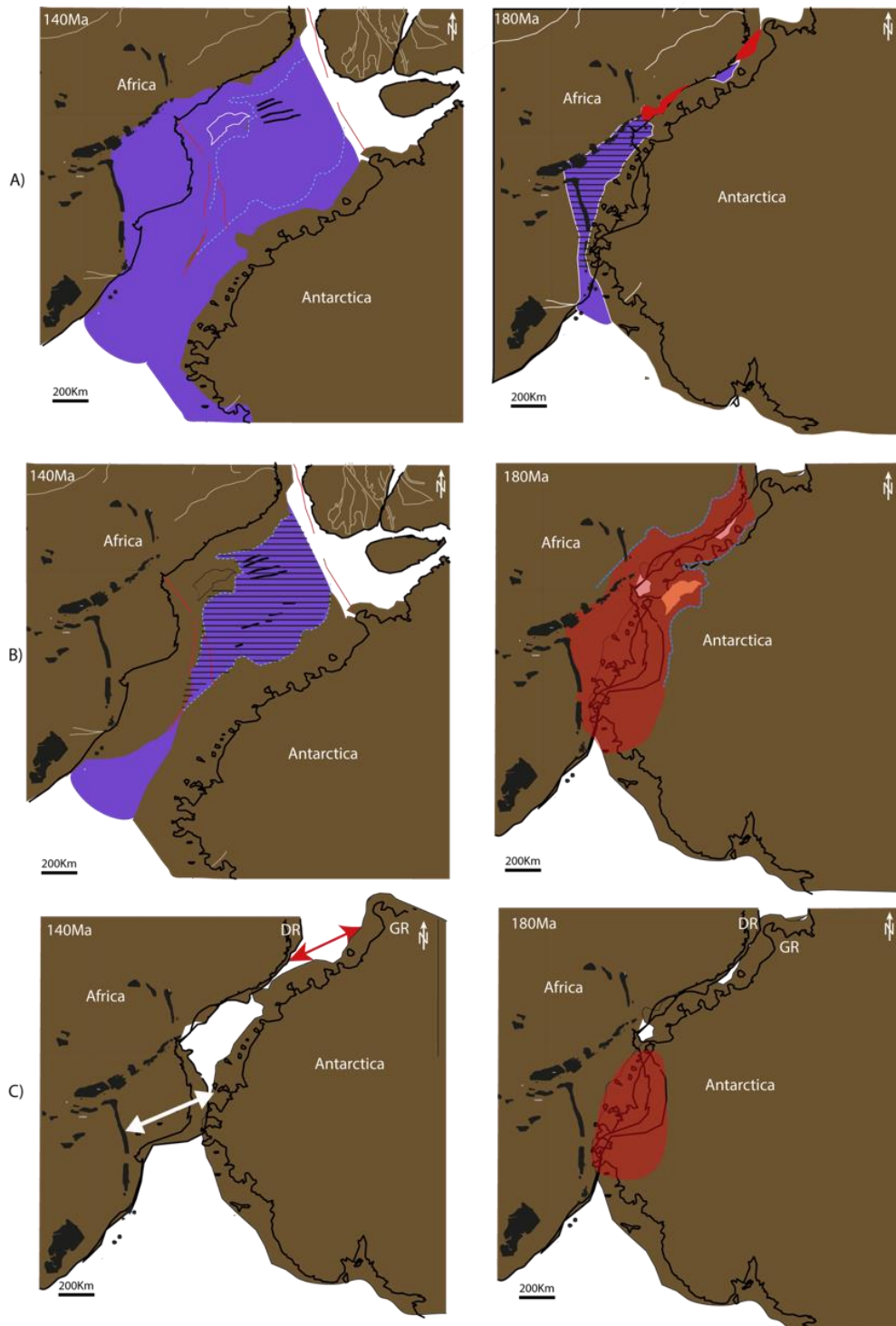


Figure 25: a) Magmatic end member scenario: The Mozambique Coastal plains are underlain by magmatic crust and the Beira High is a magmatic Plateau. When restored, the region shows regions of gap that still need to be restored as well as some small overlap b) Continental end-member: The Mozambique Coastal Plains and the northern Natal Valley are composed of a 30Km thick continental crust and the Beira High is a 25Km-thick continental ribbon. When restored, the system shows clear overlap along the whole margins. c) Early kinematic ENE-SWS extensional phase (Cox, 1992; Senkans et al., 2019). When restored gap or overlap are expected according to the nature of the MCP and Beira High but misfit of pin points (e.g. Gunnerus ridge/Davie Fracture Zone) and transfer zones orientations do not attest of this extension direction. Overlap are shown in red and gaps are shown by striped area.

5.2. Proposed scenarii

In all scenarii we use M33n (165Ma) as the first undisputed magnetic anomaly (Mueller et al., 2016). We use mainly geological pin points from the model of Davis et al., (2016) and Kristoffersen et al., (2014), which defined good structural alignments that confirm the tight fit plate reconstructions as well as the structural constraints of the Gunnerus ridge and the Davie Fracture Zone from Klimke et al., 2017. We adopt a constant extension rate between first extension and break-up.

Two scenarii consider the magmatic budget for Beira High and the Mozambique Coastal Plains. We propose end-members that are unrealistic, as expected for end-members, but which allow to discuss the importance of estimating the magmatic budget in magma-rich rifted margins linked to plume activity. Scenario 1 overestimates the magmatic addition (extrusive, intrusive, underplating) and assumes that the crust in the transition domain (green area in Figure 24) including the Mozambique Coastal Plains and the Beira High is entirely made of new magmatic material. Scenario 2 underestimates the magmatic budget and the amount of extension assuming that the transitional domain is made entirely by pre-existing continental crust.

Apart from the volume of magma, the kinematics of the early rifting phase also remains debated, although a general agreement has emerged between some more recent studies proposing a NW-SE early extension phase (Davis et al., 2016; Klimke et al., 2016; Reeves, 2018). This is in accordance with our interpretation of the regional seismic data and the observed segmentation. However, the kinematics of the different models presented by many authors are mostly dependent on the assumed nature of Mozambique Coastal plain area. In order to explore the importance of a NE-SW sinistral movement of Antarctica relative to Africa, we propose a third scenario (Figure 25, Cox, 1992; Senkans et al., 2019).

5.3. 2D and 3D crustal thickness analysis

In this section we use two semi-quantative approaches to determine the integrated crustal thickness for tight fit restorations. A first one is based on the restoration of present crustal thickness maps back to the breakup stage, a second one is based on a 2D integration of the cumulative crustal thickness along flowlines.

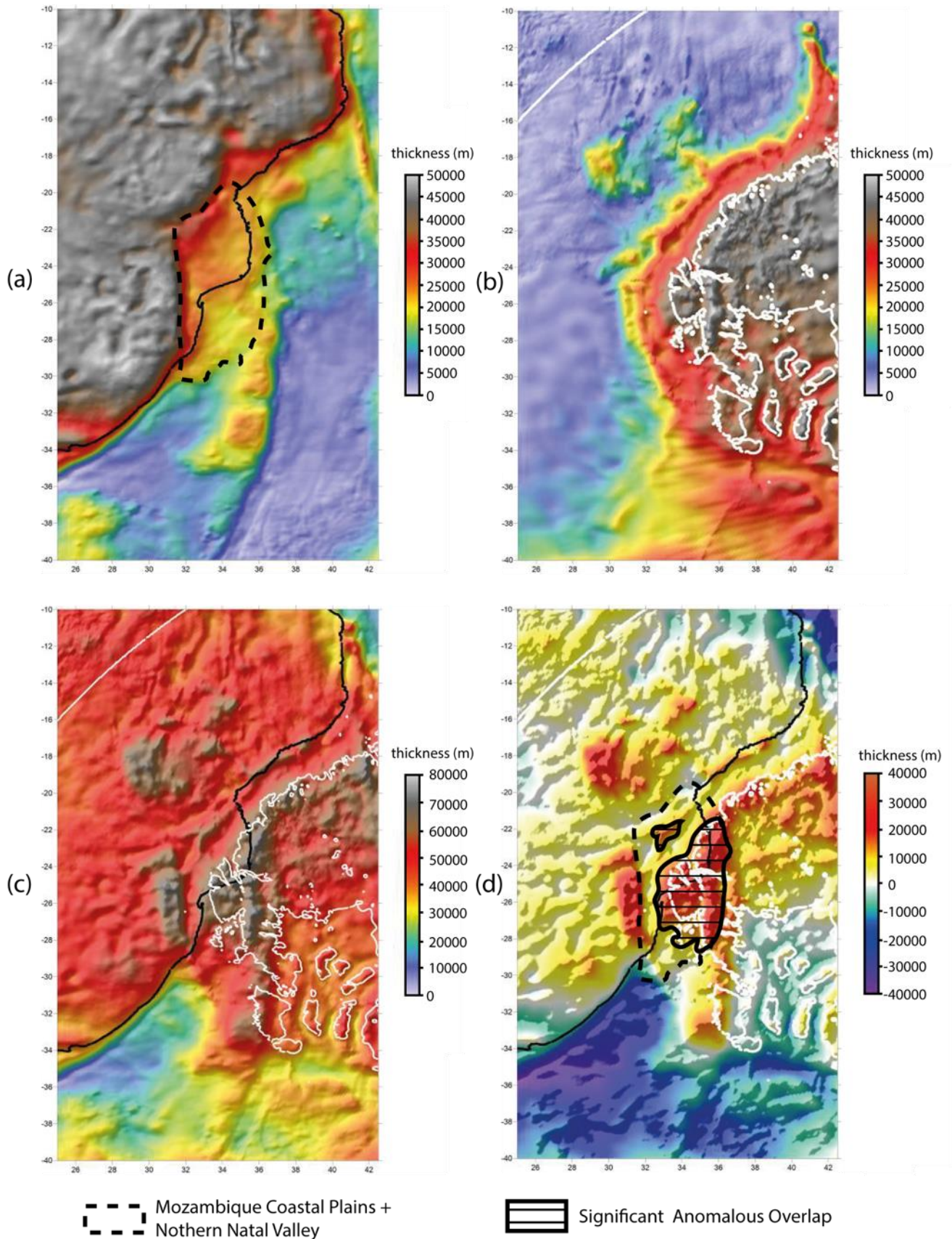


Figure 26: (a) Crustal thickness map of the Mozambique margin (data from public domain) Dashed line arbitrary bounds the Mozambique Coastal Plains and the Northern Natal Valley; (b) Crustal thickness map from Antarctica margins restored back to 177Ma with respect to Africa using Müller et al., 2008 rotation poles; (c) Crustal thickness map of Mozambique crustal thickness map (a) added to Antarctica (b) crustal thickness map; (d) Anomalous crustal thickness map where 42.5km has been subtracted from (c). 42.5km represents the sum of continental crust thickness and oceanic crustal thickness.

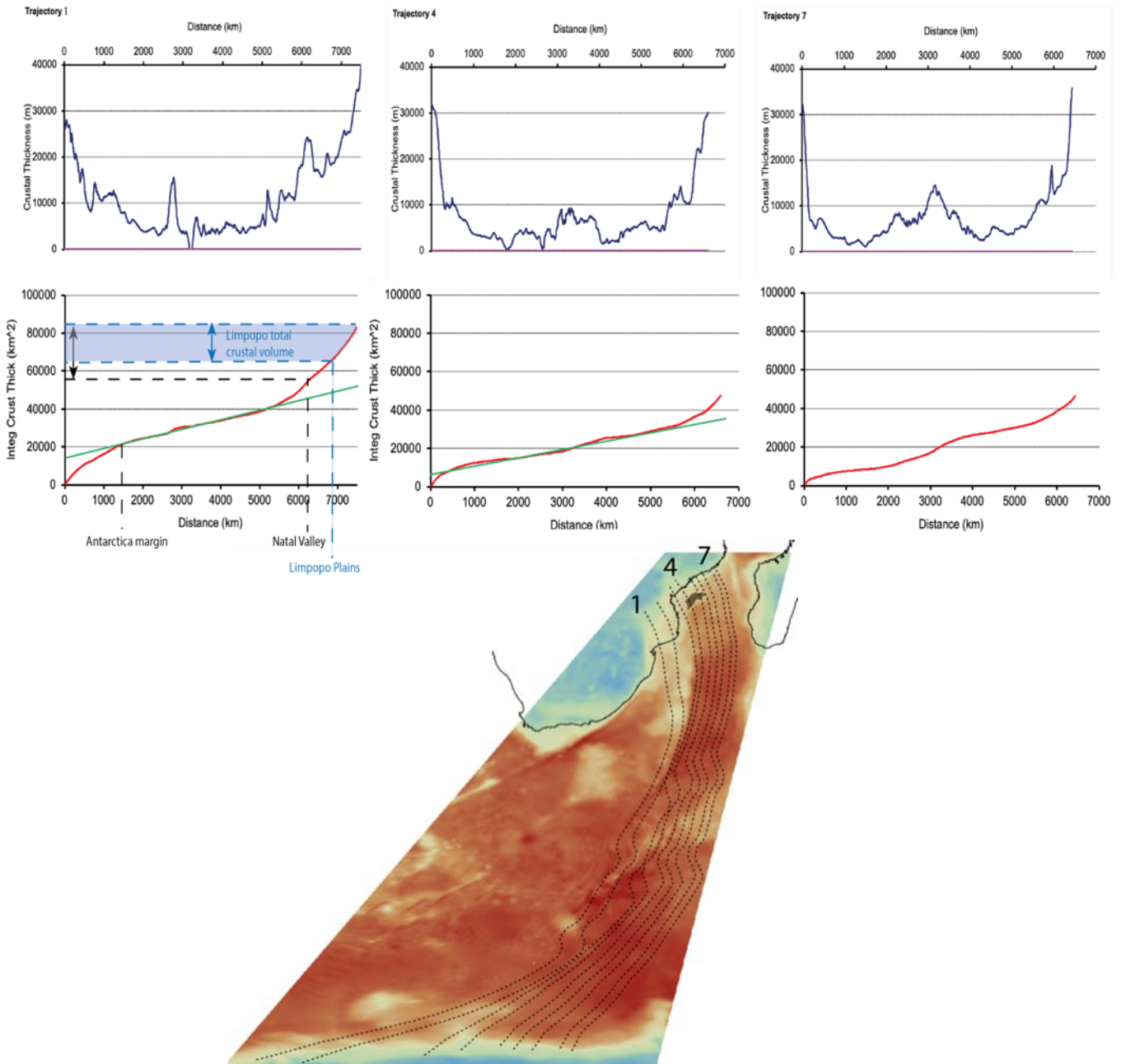


Figure 27: Crustal thickness integration results for profile 1, 4, 8. Other profiles can be seen on the map. On the graph, the green lines represent what the Integrated crustal thickness should be in a steady state oceanic crust domain. When the red curves deviate from the green lines, the crustal thickness is anomalous compared to normal oceanic crust.

5.3.1. Method 1

The first approach considers the crustal thickness maps of Mozambique and Antarctica (Figs. 6a and b) restored back to 177Ma, corresponding to the breakup from the Müller et al., 2018 global reconstruction model. We superimpose (i.e. add together) the crustal thickness (from gravity inversion) of these two maps to produce Figure 26c. At locations remote from the Continent Ocean Boundary, the superimposed crustal thickness can be

assumed to represent the sum of the original thickness of continental and oceanic crusts. These values are assumed to be 37.5 km (value used in the gravity inversion as Reference Moho Depth, see Chappell and Kusznir, 2008) for average continental thickness and 7 km for average oceanic thickness respectively giving a cumulated value of 44.5 km. To obtain a map of the anomalous crustal thickness at 177Ma, we subtract 44.5km from the superimposed crustal thickness map. The result is the Δ Superimposed Crustal Thickness (ΔS) shown in map (Figure 26d) that we interpret as the approximate thickness of magmatic additions. In Figure 6d we highlight the region where the anomalous thickness is most significant (>20km thick) by the dashed polygon. It overlaps with the Mozambique Coastal Plains and the Northern Natal Valley (dashed polygon, Figure 26a and d). Areas outside this zone with high anomalous crustal thickness (in red, Figure 26d) could be related to younger magmatic events. The negative anomalies (in blue) are explained by the failure to properly restore Ewing Bank and other continental material, which is beyond the scope of this study. This approach allows us to identify a significant restored crustal thickness anomaly (~25 km) in the Limpopo Plains that corresponds to magmatic addition.

	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8	Profile 9
Length of the profile:	7490.98376	7364.23092	6731.69579	6593.78364	6402.7405	6446.1595	6428.9539	6304.39335	6411.17827
Integrated Total Crustal Thickness:	83055.3625	83323.6073	57067.1728	47481.1307	43530.1985	44978.0209	46390.9805	46041.3697	49980.6755
Intregated total extension:	5748.08572	5697.70189	5772.16524	5893.99141	5877.43024	5822.02183	5764.48562	5627.28703	5631.07472
Mean value of integrated crustal thickness:	Limpopo: 83189.4849			Beira: 45329.7834			Angoche: 47471.0086		
Normalised Crustal thickness to profile length:	11.0873772	11.314638	8.47738438	7.20089304	6.79868229	6.97749115	7.21594543	7.30306108	7.79586425
Mean value of normalised integrated crustal thickness:		11.2010076			6.99235549			7.43829025	

Table 1: Result of 2D crustal thickness integration. The box coloured of “Mean Value of integrated crustal thickness” is the mean value of the “Integrated Total crustal thickness” of the same colour. By this calculation, we obtain one average value per margin segment. We also normalised it to the length of the profile to check the importance of profile lenath. The ratio between seament remains the same even when normalised.

5.3.2. Method 2

In the second approach we use a 2D method integrating the crustal thickness along flowlines from one margin to its conjugate (Figure 27). The ends of these flowlines are the unambiguous proximal margin continental crust defined earlier that has been chosen as an arbitrary limit (see map Figure 27). The flowlines are separated by segments (see colors in Table 1): Limpopo segment (blue), Beira segment (orange), Angoche segment (green). By comparing the crustal thickness integration curve to the line representing the integration of the crustal thickness of steady state oceanic crust, we highlight where and how much excess material exist in the basin along the profile. The overall integration shows a much larger

amount of crustal material on the Limpopo Segment. We also normalized the integrated crustal thickness by dividing the result by the length of the profile in order to be length-independent. The normalized integrated crustal thickness shows values for the profiles of the Limpopo segment which are twice the amount of integrated crustal thickness of the other segment profiles. These Limpopo segment values, have, however, to be carefully considered because the flowlines also cross the southern Mozambique ridge (which is built by post-tectonic magmatism). The annotations on trajectory 1 integrated crustal thickness graph shows the proportion of material due to the Mozambique Ridge, the amount due to the MCP and the Northern Natal Valley. The crustal thickness in the NNV, and in particular, in the MCP, are relatively high ($\gg 20\text{km}$) and, therefore, the restorable portion of the crust should be low in this region (according to the method in Nirrengarten et al., 2018). Thus, a large proportion of the exceeding material in the MCP and NNV has to be magmatic, otherwise the restoration at M33n would show large overlaps.

6. Discussion

Fits and misfits: towards a best fit scenario:

In scenario 1 the Mozambique Coastal Plains and the Beira High are modelled as entirely magmatic. They represent new crust that did not exist prior to rifting, and, as a consequence, can be ignored in the kinematic restoration. In this scenario, the reconstructed Antarctica-Mozambique fit is the tightest (Leinweber and Jokat, 2012; Davis et al., 2016). At the Gunnerus/Davie Fracture pin point (presented in Klimke et al., 2017) as well as at the Maputo Pin Point the reconstruction fits completely. Antarctica is almost entirely overlapping the Mozambique Coastal Plains up to the limit of the SDRs and the Beira High area (~388Km of overlap, Figure 25b). This is in line with the interpretations of Leinweber et al., 2013; Davis et al., 2016; Davison and Steel, 2018; Mueller and Jokat, 2019). Although they do not stipulate the nature of the basement, they show, from seismic interpretation and well analysis, a section where extrusive magmatic materials are widespread over the Mozambique Coastal Plains. These flows are believed to be associated with the Lebombo monocline and are interbedded with sandstones and capped by Cretaceous marine sediments underneath marine shales from the Domo formation (Davison and Steel, 2018). On seismic reflection line MBWG13-100, we see high amplitude parallel reflectors westward

of the transform escarpment. We also notice the wavy seismic facies that might be linked to intrusions. Finally, we clearly observe a gap in the northernmost part of the Mozambique Coastal Plains that can't be restored (Figure. 5a). This is possible evidence for the existence of the crustal block of Limpopia, which could fill the gap (Reeves, 2018). Although some authors proposed the Mozambique Ridge to be entirely magmatic (Fischer et al., 2017), the over-constricted area in the eastern part of the basin and the gaps in the northern Mozambique Coastal Plains, the Northern Natal Valley and the Mozambique Coastal plains suggest that the crust in these areas cannot be entirely magmatic and new crust.

Considering the Beira High as a volcanic Plateau, as suggested in scenario 1, would imply the existence of a later phase of extension to explain the tilted blocks observed on the southern Beira High. The age of these faults and the related syn-tectonic sedimentary wedges would be, according to the G-plate reconstruction, post-Calloviaian (162Ma). This tectonic event would have been followed by another magmatic phase as suggested by the observed magmatic edifices sealing the faulted surface (Figure 22b).

In scenario 2, the Mozambique Coastal plains and the Beira High are assumed to consist of entirely continental crust. In such a scenario, the Mozambique Coastal Plains cannot be overlapped by Antarctica. A continental origin of the Beira High has been proposed by Mueller et al., 2016, based on the interpretation of the basement refraction velocities. These authors interpreted the Beira high as intruded continental basement. Such interpretations are not irrefutable as the refraction velocities could also be characteristic of mafic magmatic material (6.8 Km/s). If the NW-SE opening is preserved, this results in an obvious gap in the Angoche segment of over ~300km and of ~110km south of the Beira High. Such gaps could be partly filled by rotating the Antarctica plate, although this leads to a misfit of the different pin points. Moreover, considering the southern limit of continental crust in the Natal valley (Thompson et al., 2019), we need to be able to restore over 1000km of continental crust, which is between 40km and approximately 10km thick along a flowline through the Mozambique Coastal Plain, which is difficult, if not impossible.

In scenario 3, we consider an initial ENE-WSW sinistral initial movement of Antarctica relative to Africa (Cox, 1992; Senkans et al., 2019). In this scenario, both a magmatic or a thinned continental crust can floor the Mozambique Coastal Plain, we are only interested in the kinematic aspect and how does it fit with the regional pin points. On one hand, the extension leading to the thinning of the continental crust could have occurred while

Antarctica is moving eastward. The Lebombo monocline may have formed during an initial ENE-WSW directed movement and might be conjugate with the Explora Wedge as we observe there a N-S striking monocline and westward dipping SDRs too. On the other hand, the Gunnerus/Davie Fracture pin point is, however, not respected. Also, the question remains if the overall extension of the Mozambique Coastal Plains can be explained by the sinistral movement or if it is a part of the later NW-SE extension. Moreover, beside the N-S trending Lebombo monocline, the observed segmentation of the margins (i.e., the actual orientation of the transfer zones) would rather suggest a NW-SE extension as the transfer areas east and west of the Beira High are NW-SE oriented. Therefore, this scenario could be consistent with a small E-W extension, however, it doesn't determine the nature of the Mozambique Coastal Plains basement.

The analysis of the three scenario shows that none of them can satisfy the main observations and explain the tightest fit. The "magmatic crust" scenario 1 resulted in a gap in the northern Limpopo area and some less-significant overlaps along the Beira to Angoche margins. The "continental crust" scenario 2 produces major overlaps along the whole margin. Thus, a most likely situation is the existence of a hybrid crust, i.e. a combination of scenarii 1 and 2. Such a combination can, however, not explain some of the first order observations, such as N-S trending Lebombo monocline which are consistent with scenario 3. The third scenario does not bring detailed quantification concerning the E-W kinematics however within the more regional framework the geological pin points (Gunnerus Ridge and Davie Fracture Zone as well as far field pin points; see Davis et al., 2016) limit the magnitude of the E-W extension. Thus, our preferred scenario consists in an early, but limited E-W movement of the Antarctica plate relative to the African plate that had to occur simultaneous to magmatic activity which then persists during the subsequent NW-SE movement.

In addition to the kinematics, the question about the relative amount of magmatic vs inherited crust forming the Mozambique Coastal Plains is essential to explain the evolution of the Mozambique Channel. First order 2D quantitative analysis (Figure 27) show that the proportion of magmatic addition versus inherited continental crust beneath the Mozambique Coastal Plains has to be at least 1 to 1. The 3D approach based on the overlapping of crustal thickness maps (Figure 6) shows that the magmatic additions are located mainly on the outer Mozambique Coastal Plains. In the superimposed maps, this

region corresponds, on the Antarctica side, to the location of the Grunehogna Craton. From what we can see in all examples on the better understood African side, magmatic additions seem to occur preferentially at the extremities of the craton (see Figure 21a). Thus, we do not expect much magmatic addition on the Antarctica side. The estimation of the ratio between new magmatic vs. inherited continental crust has major implications, especially for the seismic interpretation (see interpretations in Figure 22). Indeed, our results ask us to consider a lot of more magmatic additions on the seismic lines as formerly expected. In order to explain an average 30km thick basement flooring the Mozambique Coastal plains, we need to consider up to 15km of magmatic material including intrusive and extrusive volcanoclastic material.

A best fit scenario for the Mozambique Antarctica rift system and implications

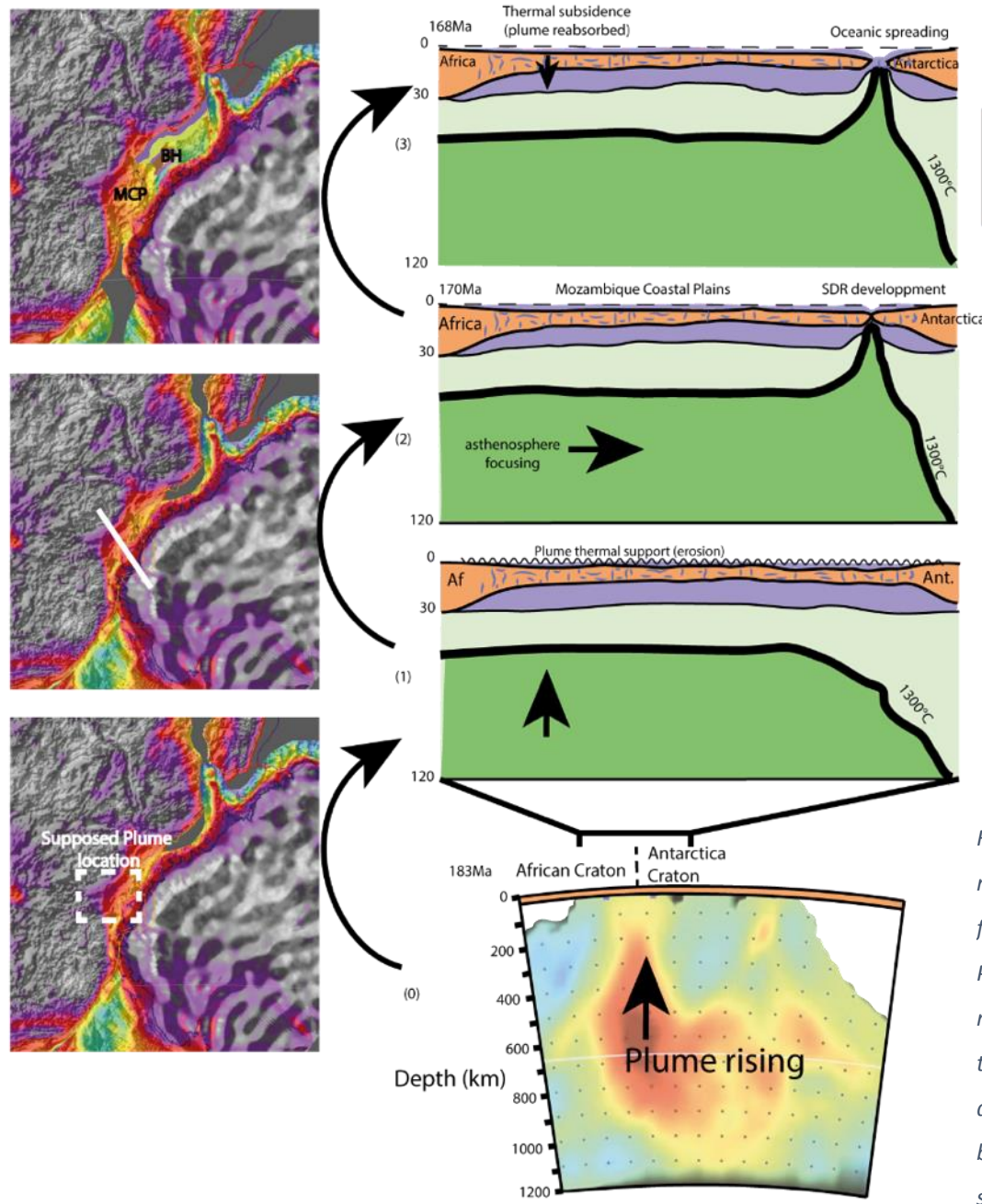
Based on the evaluation of the different scenarii, the quantification of the ratio of magmatic additions over continental crust and the seismic reflection observations the following, best fit, three phase model can be proposed to explain the evolution of the Mozambique-Antarctica conjugate rift system (see Figure 28).

In an initial phase magma production, triggered by the Karoo plume, occurs simultaneously with the beginning of E-W directed extension. The occurrence of severe syn-extensional magmatism implies that crustal thinning is compensated by magmatic additions. Thus, despite thinning of the initial continental crust, addition of extrusive, intrusive and underplated magmatic material can maintain the crustal thickness approximately constant. Thus, during this stage continental crustal thinning needs to be similar to the volume of magmatic additions. As a consequence, the top and base of the new hybrid crust are parallel and the top basement and crustal base (Moho) are new and magmatic. Thus, the thickness of the bulk crust (inherited continental plus magmatic crust) does not decrease, despite major extension. The magmatic addition includes mafic underplating, intrusive material and extrusive flows (constructive edifices, parallel infill, or SDR) that are syn-tectonic. The spatial extent of the domain that was affected by this first phase might be up to hundreds of kilometres in lateral extent and may depend on the magmatic budget, the rate of extension, but might also have been controlled by inheritance that may have controlled and deviated the plume heat underneath the domain into which final rifting localized (Koptev et al., 2016). While this domain was at or near sea level during its formation, subsequent thermal

equilibration resulted in subsidence and creation of post-rift accommodation space, explaining the 3 to 5km of sediments covering the present-day Mozambique Coastal plain. This phase leads to a type of crust that is difficult to assess and to characterize by geological and geophysical methods and only the combination of quantitative analysis and restorations may be able to identify the nature of such a crust. In this study we used a combined geophysical/geological approach to estimate the ratio between thinned continental and magmatic crust. The 3D qualitative and 2D quantitative approaches are presented in (Figure 26 and 27) and show a ratio of 50% of continental crust and 50% of magmatic crust. The main problem, however, is that present imaging does not allow to distinguish between magmatic additions and inherited continental crust, and to support the predicted syn-tectonic nature of the magmatic additions.

During a second phase, during which extension was NW-SE directed melt production decreased relative to crustal thinning and deformation and magma localized towards the area of future breakup, likely responding to a localized rise of the asthenosphere at the edge of a wider area affected by the plume dynamics. The tectono-magmatic evolution and the concomitant thermal support of the rising asthenosphere may have provided the sub-areal conditions to form the SDR sequences. The observation of erosional unconformities over the SDRs on the Mozambique Coastal Plains, the Beira high, and some other crustal blocks observed on seismic lines (Figure 22) further endorse a thermal support due to plume dynamics. Inception of the transition toward thermal subsidence occurs during final rifting as indicated by the onlapping of marine sediments. The characteristic of the domain that formed during this event is that top and base of the crust are clearly converging oceanward. How the crust thins during this stage, where is its limit and what is the relationship between inherited crust and magma in the sections across the margin remain, however, difficult to evaluate.

During a final stage, the crustal thickness stabilizes as indicated by top and base of new crust that are parallel, suggesting steady state, constant magmatic production reminiscent of seafloor spreading processes. Oceanic crust forms as the shape of the basement tends to a normal parallel top and base of crust (c.f. steady state oceanic crust). In the Mozambique Channel, the distance from the first thicker oceanic crust to normal thickness oceanic crust of 7 ± 1 km occurs over about 600km.



Chapter II: The challenge in restoring magma-rich rifted margins

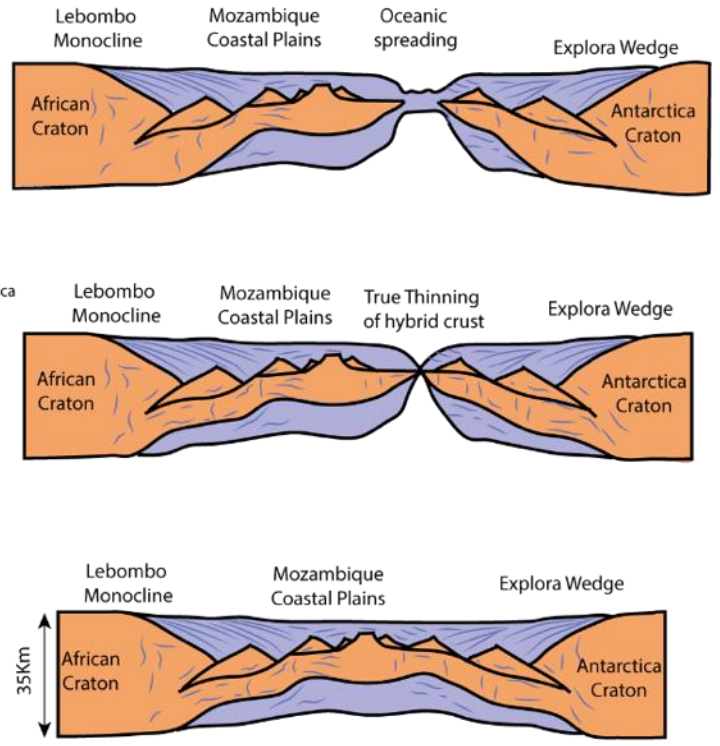


Figure 28: Schematic evolution of the Mozambique-Antarctica magma-rich extensive system. (0) Tomography picture is shown here for a scale indication of a mantle plume after Koptev et al., 2015. (1) Plume is rising, producing melt as the lithosphere is thinned. This magmatic addition maintains crust to a certain thickness balancing the crustal thinning. (2) The magmatic pulse is over, SDRs may develop. (3) Lithospheric breakup occurs and oceanic spreading begins. Maps indicates the associated plate reconstruction. Crustal scale interpretations are inspired from Foulger et al., 2019.

7. Conclusion

In this study, we describe and map rift domains, propose a new rift domain map with 3 main domains referred to as unambiguous continental crust, Penrose oceanic crust and transitional/debated crust. Based on this interpretation we highlight some key areas of uncertainty in the transitional domain (Mozambique Coastal Plains, Beira High) that cannot be discriminated by the nature of its basement and the kinematics. We develop end-member scenario, none of which provide perfect agreement with observations. If the Mozambique Coastal Plains is made only of continental crust it results in an enormous gap on the Angoche segment; if it is made entirely of magmatic material it leaves no room to restore the Beira High, and if a major NE-SW sinistral movement is assumed during the early stage of extension it can explain the N-S Lebombo monocline described as SDRS but results with a misfit of the Gunnerus/Davie pin point.

In this study we propose a best fit scenario to explain the evolution of the Mozambique Channel, which is between the three tested ones. This scenario proposes that the rift system is complex in terms of estimating the magmatic addition, however we can approximate the proportion of magmatic addition at 50% versus continental crust at 50% by using a 3D and 2D analysis. We assume an E-W directed extension for initial rifting, however, the amount of this extension must be limited in order to not get misfits at the Gunnerus/Davie pin point. Such an approach can minimize the gaps and overlaps and is compatible with the overall observations.

In summary we describe the evolution of the Mozambique extensional magma-rich system by a three stages model: i) Karoo plume related magmatism peaks at the very beginning of extension and fills the accommodation space created by thinning resulting in a crust that remains thick; ii) the magmatic budget relatively decreases compared to extension rates leading to the thinning of the bulk crust, during continuous thermal support and creation of SDRs; iii) Transition to oceanic crust that initially is relatively thick as the magmatic budget remains high compared to normal oceanic crust and eventually transitions to steady state normal thickness ($6,5\pm 1\text{km}$) oceanic crust. The approach and methods used in this paper may be applicable to other mantle plume related margins to understand how far they are impacted by magmatism and what are the nature of ambiguous domain.

In the second chapter, through the analysis of end-member scenarii, I highlight the impossibility for the Mozambique Coastal Plains and Beira High to be entirely igneous nor entirely continental crust. I propose that these domains are floored by hybrid crust which correspond to thinned continental crust with huge amount of magmatic addition. In the next chapter, I defined the main characteristics of the proposed model of hybrid crust, and verify that the MCP answers to these characteristics via 3 geophysical approaches.

Chapter III: Hybrid crust: a
geophysical and geodynamic
analysis of the magma-rich
Mozambique E-African margin

Hybrid continental-magmatic crust at rifted continental margins: A geophysical and geodynamic analysis of the magma-rich Mozambique E-African margin

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Abstract:

Observations show that rifted margins formed adjacent to an active mantle plume are highly magmatic. The resulting combination of remnant thinned continental crust with large volumes of magmatic addition produces a hybrid crust. Such hybrid crust formed at rifted margins should possess a particular combination of characteristics. These include a relatively smooth unfaulted top basement, SDRs or evidence for sub-aerial exposure and erosion, thick crust with sub-parallel top basement and Moho, a crustal density higher than typical continental crust, thick post-rift sedimentation which is anomalous with respect to its crustal thickness.

In this study, we investigate the Mozambique Coastal Plains (MCP) and Beira High (BH), located on- and off-shore Southern Mozambique margin, which are expected to be underlain by hybrid crust and to have some or all of the expected characteristics. We use quantitative geophysical and geodynamic analytical, in addition to observed geology, consisting of: 1) regional 3D gravity inversion to observe the regional crustal thickness for the southern Mozambique margin, its pattern and trends, 2) a comparison of seismic refraction Moho and Moho from gravity inversion to determine crustal basement density of the suspected hybrid crust with respect to that of adjacent oceanic crust, and 3) post-rift subsidence analysis to determine lithosphere thinning and the thickness of remnant continental crust.

Our results show that the MCP and BH have the characteristics of hybrid crust. Their basement densities for both are greater than that expected for continental crust only and require a significant contribution from denser magmatic material. The basement density of the MCP is in excess of 2950 kgm^{-3} implying a significant contribution from picritic magmatism consistent with proximity to a mantle plume. Post-rift subsidence analysis for

the top SDRs of the MCP predicts that of the thickness of underlying remnant continental crust is between 15 and 25 km, the remainder consisting of magmatic addition.

1. Introduction

Present-day classifications of rifted margins often use the concepts of magma-poor or magma-rich margins. However, in reality most margins appear to be hybrid margins showing characteristics of both magma-rich and magma-poor margins. In particular in margins where crustal thinning occurs at the same time as large amounts of magma production, it is difficult to image and describe the nature of the resulting hybrid crust and to constrain, in detail, the processes linked to their production. Hybrid crusts result from the combination of two processes: extension and melt production. However, defining the relative proportion of inherited, thinned continental crust and new igneous crust is very difficult from the interpretation of seismic reflection sections. Extrusive magmatic additions often mask the nature and structure of the underlying crust. In such examples, information is not available from seismic interpretation to produce rift domain maps, to evaluate rifting histories and to determine tight fit kinematic plate restorations. Many studies have discussed the nature of the basement underlying magmatic additions as well as the magmatic budget and the relative proportion of magmatic crust with respect to inherited continental crust (Charvis and Operto, 1999; McDermott et al., 2015; Tugend et al., 2018; Magee et al., 2018; Harkin et al., 2019). The study of such a “hybrid crust” in a magma-rich margin setting based on seismic reflection or refraction interpretations only is therefore difficult, since the seismic properties of igneous rocks are in the range of continental basement crustal rocks commonly forming the inherited continental crust. Thus, the use of seismic reflection and refraction methods alone cannot provide definitive answers to constrain the nature of hybrid crust in magma-rich margin settings.

Hybrid crust typically shows thinned inherited continental crust that has been thickened by syn-tectonic magmatic. If there is sufficient magmatism then extrusive magmatic systems can fill up the accommodation space formed by crustal thinning and thick sub-areal magma emplacement results which masks the underlying crustal extension. Extrusive magmatic additions are associated with high density intrusives and underplated magmatic additions that form their magmatic plumbing supply systems which are poorly

understood for hybrid crust. The formation of such crust, which is common in mantle plume settings, is accompanied by both thermal and dynamic uplift support, followed by subsequent thermal and plume collapse subsidence.

Hybrid crust is characterized by three main geological characteristics (see Figure 29) : 1) inherited, thinned continental crust sandwiched between extrusive and intrusive-underplated magmatic additions, 2) due to the combination of “mantle plume” dynamic uplift and syn-rift thermal support, hybrid crust has a distinct isostatic evolution with very

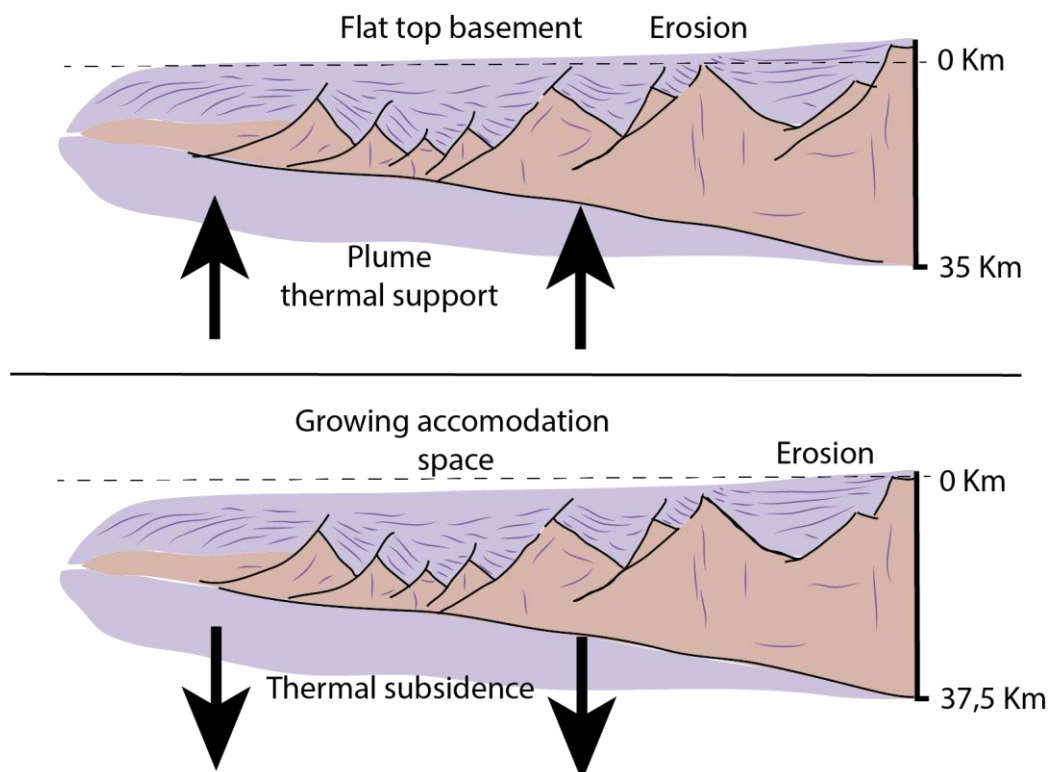


Figure 29: Schematic section showing the main characteristics of hybrid crust (i.e. continental crust + magmatic addition). Most important characteristics are the flat and parallel top basement and base crust., the accommodation space created due to thermal subsidence after the plume resorbs, the plumbing of the crust by shallow bathymetry at first then substantial deepening leading to the apparent anomaly of a large sediment thickness above relatively thick crust, 3) the presence of hybrid crust results in conflicting kinematic plate reconstructions prior to breakup because of the difficulty of making a tight-fit due to the unknown amount of “new” magmatic crust

The main question addressed in this study is can we use geophysical and geodynamic approaches to determine the geological characteristics of such “hybrid” crust. In our study we use the example of the Mozambique Coastal Plains (MCP) and Beira High (BH). I combine several different approaches to analyse the MCP and BH comprising:

- i) crustal thickness mapping using gravity inversion, with sediment thicknesses derived from industry seismic reflection datasets, to examine its distribution and the location and orientation of structures.
- ii) determining basement density differences between hybrid and oceanic crust using gravity inversion constrained by seismic refraction Moho depth, and
- (iii) subsidence analysis to determine lithosphere thinning and the thickness of remaining continental crust.

2. Geological Setting

The Mozambique Coastal Plains (MCP), the Northern Natal Valley (NNV) and the Beira High (BH) have been the focus of recent debates about their crustal nature. Leinweber and Jokat, (2012) proposed that the MCP and the NNV are entirely floored by oceanic crust while (Hanyu et al., 2017; Thompson et al., 2019; Moulin et al., 2019) proposed that these domains are made entirely of continental crust. As a consequence, the Continent Ocean Boundary (COB) of the different interpretations and the corresponding plate restorations to pre-breakup are in disagreement.

The opening of the Mozambique Channel is associated with a surge of the Karoo/Bouvet mantle plume and its magmatism. Massive magmatic addition spread widely over the region and mask the structure and nature of the crust. Magma emplacement was simultaneous with the initial E-W motion of the future Antarctica plate relative to Africa (Cox, 1992; Senkans et al., 2019). These early movements are considered to be responsible for the N-S trending Lebombo Monocline (Klausen, 2009). During the following early NW-SE motion of Antarctica relative to Africa fixed, the MCP crust was extended.

Tomasi et al. *subm.*, proposed, based on the evaluation of end-member scenarios, that the MCP and NNV domains are floored by hybrid crust consisting of thinned continental crust together with magmatic additions. In the same study, they evaluate different end-member scenarios and conclude that the best fit restoration can be obtained by using a hybrid crust in the Mozambique Coastal Plains and the Northern Natal Valley. The authors propose that syn-extension magmatism compensates the crustal thinning resulting in a post-rift hybrid crustal thickness >30km thick crust. By restoring the crustal thickness map they estimate approximately equal proportions of new magmatic addition (extrusive +

intrusive or underplating) and inherited thinned continental crust. The magmatic addition is associated with the Karoo/Bouvet plume which is approximately around 183Ma (Mueller and Jokat, 2017, see also Figure 30). The volcanic flows extend along the E-W trending Mozambique margins in particular in the Zambezi depression north of the Beira High. Mahanjane, (2012) observed the aborted rift north of the Beira High and the magmatic nature of the basement in the Zambezi depression. The Beira High is clearly affected by intrusive and extrusive pre- and post-breakup magmatism. The first magnetic anomaly, providing constraints for the age of lithospheric breakup is M33N (~ 161 Ma) in the eastern part of the basin dated. At 154Ma, the oceanic spreading shifted to N-S (Leinweber and Jokat, 2012; Leinweber et al., 2013; Davis et al., 2016).

3. Analytical Methodology and Data Used

In this study, we use three quantitative geophysical and geodynamic approaches to examine the nature of the hybrid crust under the MCP and BH. These approaches are:

- 1) Gravity inversion to determine 3D Moho depth and crustal basement thickness using sediment thickness derived from seismic reflection interpretation,
- 2) Combined inversion of gravity data with seismic refraction Moho depths to determine 2D basement density along the refraction profiles, and
- 3) Analysis of post-tectonic subsidence of the SDR horizon in the MCP to derive continent lithosphere thinning and the residual thickness of rifted continental crust.

3.1. 3D Moho depth and crustal basement thickness from gravity inversion

A detailed description of the gravity inversion method can be found in Greenhalgh and Kuszniir, (2007), Chappell and Kuszniir, (2008), Alvey et al., (2008), Kuszniir et al. , (2018). The gravity inversion method is carried out in the 3D spectral domain and incorporates a lithosphere thermal gravity correction (which in this case of an old thermally re-equilibrated continental margin lithosphere is not large). For the assumptions made (see Chappell & Kuszniir 2008), the gravity inversion method produces a unique solution for 3D Moho depth by invoking Smith's theorem (197?). The input data required for the gravity inversion is 3D bathymetry, free-air gravity anomaly and sediment thickness. We use public domain bathymetry and free-air gravity data. Sediment thickness data is derived from the interpretation of the TOTAL regional seismic reflection data-set presented in Tomasi et al.,

subm. This seismic refraction data-set was acquired by WesternGeco using a slanted-streamer broadband with a long-offset 10km streamer and has been processed by an anisotropic Kirchhoff pre-stack time migration. An important parameter used in the gravity inversion method is Reference Moho Depth (RMD)(Cowie et al., 2015). We calibrate the RMD using Moho depth determined from refraction seismology on oceanic crust; for the 3D mapping an RMD of 35 km is used. For the calculation of the lithosphere thermal gravity anomaly correction, oceanic lithosphere cooling times are derived from the ocean isochrons of Mueller et al (2018). A breakup age of 165 Ma is used to for the cooling time of rifted continental margin lithosphere. For this 3D mapping a crustal basement density of 2850 kgm^{-3} is used.

We use this approach to examine the distribution of crustal thickness of the southern Mozambique margin across the OCT from proximal to distal and its variation along strike, focusing on the MCP and BH.

3.2. Lateral variation of crustal basement density from gravity inversion and refraction seismology

The second approach, which determines the lateral variation of basement density, compares the Moho depth derived from gravity inversion and seismic refraction Moho

Upper crust 13.7 km Middle crust 13.0 km Lower crust 12.1 km Upper crust density $2,700 \text{ kg/m}^3$ Heat production $1.58 \text{ } \mu\text{W/m}^3$ Mantle heat flow $11\text{--}18 \text{ mW/m}^2$	Most- mafic middle and lower crust	Fastest- V_p middle and lower crust	Most-felsic middle and lower crust	Slowest- V_p middle and lower crust	Lower, middle crust the same
Upper crust (wt%)	32	33	34	34	33
Middle crust (wt%)	34	33	33	33	34
Lower crust (wt%)	34	34	33	33	33
Crustal density (kg/m^3)	2,950	2,904	2,786	2,789	2,864

Table 2: Properties of different kind of crust after Hacker et al., (2015). Here we are mainly interested in the bulk crustal density and compare it to the calculated density from the joint inversion.

depth. The refraction Moho depths used were those determined from the IFREMER MOZ campaign for and adjacent to the MCP (Moulin et al., 2019) and from Mueller and Jokat, (2017) for the Beira High and Mozambique margin to the east. The gravity inversion method

is similar to that used in approach 1 except that the sediment thicknesses used were derived from the refraction seismology. A first-pass gravity inversion was performed using a constant basement density of 2850 kgm⁻³. The resulting Moho from gravity inversion is then compared with the refraction Moho and the basement density is then adjusted laterally to produce a gravity inversion Moho that coincides with the seismic refraction Moho. This approach, for the assumptions made, preserves the uniqueness of the gravity inversion method. Sensitivity tests to the RMD were carried out using values of 35 and 32.5 km.

We use this second approach to determine the difference between the crustal basement density of oceanic crust and that of the MCP and BH. by comparing the inverted Moho depth result to the refraction Moho (joint inversion method). These densities are also compared to the densities of different type of crust (see Hacker et al., (2015) and Table 2).

3.3. Subsidence analysis to determine thinning and the thickness of residual continental crust

The third approach used in this study is a subsidence analysis to determine continental lithosphere thinning on the MCP. We assume that SDRs on the MCP have subsided by post-rift thermal subsidence and use flexural backstripping (using Flex-Decomp software) to determine their water loaded subsidence from their formation to the present day. This water loaded subsidence is then converted to lithosphere thinning factor $(1-1/\beta)$ using the McKenzie model (1978).

The present day depth of top SDRs is obtained from the E-W cross-section drawn by Davison and Steel, 2018 crossing the entire Mozambique Coastal Plains. The section, is calibrated by the Domo-1 well (Figure 34). Top basement is basaltic material, interpreted as SDRs, from the Lebombo Monocline to the eastern limit of the MCP. We test different ages for the top SDRs (see supplementary material). 180Ma is the oldest limit of the SDRs based on the average age of the Lebombo monocline. 130Ma is the younger limit defined by the age of the southern Mozambique Ridge plateau (Fischer et al., 2017). The GPlates reconstruction suggests an intermediate age of 150Ma for the emplacement of the basalts and we use this for the age of top SDRs in the subsidence analysis.

We assume that the SDRs were at or near sea-level for the determination of water loaded subsidence from flexural backstripping. The excess magmatism associated with the

SDR formation is very likely associated with mantle plume activity and plume dynamic uplift. As a consequence, SDR subsidence to present day will be due to not only post-rift thermal subsidence but also the collapse of mantle plume uplift collapse. We determine lithosphere thinning from subsidence analysis for 0.0, 0.5 and 1.0 km of plume uplift collapse to explore the sensitivity to this parameter.

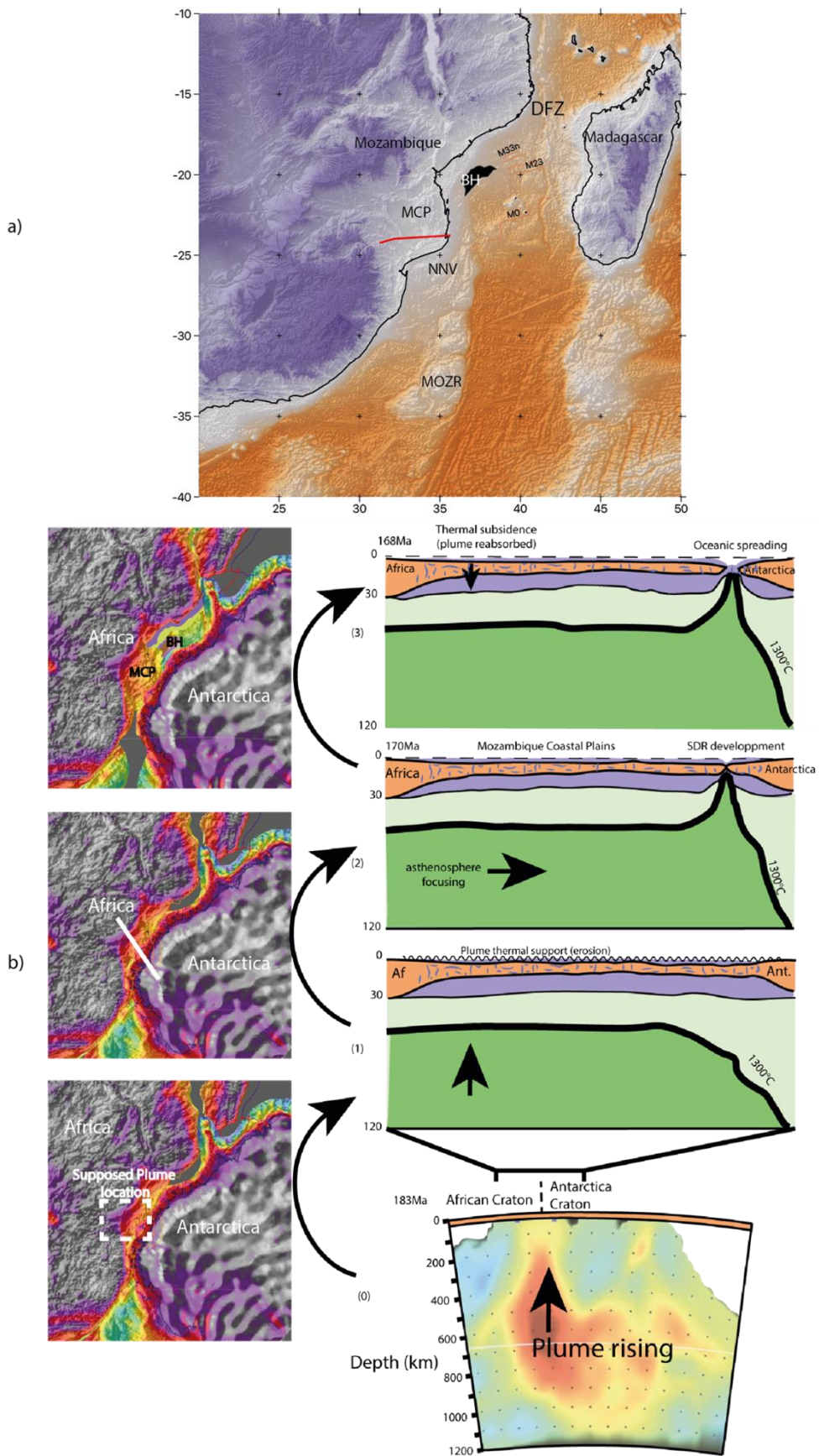


Figure 30: a) Bathymetry of the Mozambique Channel showing the main features and regions analyze in this study. b) Evolution of the Mozambique Coastal Plains associated to the Karoo/Bouvet Plume showing the formation of hybrid crust by the high proportion of magmatic addition.

The resulting lithosphere thinning factors from subsidence analysis are used to estimate the remnant thickness of thinned continental crust under the MCP.

4. Results

4.1. The regional distribution of crustal thickness from 3D gravity inversion

We show the regional crustal thickness map produced by 3D-gravity inversion to highlight regional trends and main features in Figure 31a. For the large-scale regional mapping of crustal basement thickness, public domain sediment thickness data have been used in the gravity inversion. Figure 31b and c show crustal thickness and Moho depth determined from gravity inversion using more detailed and accurate sediment thicknesses derived from seismic reflection interpretation for the region focused on the MCP and BH. This more detailed crustal thickness map is superimposed on the regional map shown in Figure 31a.

The eastern boundary of the studied area is clearly identified in Figure 31a by the N-S trending Davie Fracture Zone that constrains the large-scale plate kinematics. On the eastern segments of the Mozambique margin we observe a sharp transition from 30km thick crustal basement to <10km thick oceanic crust. Between the Mozambique Ridge and the Madagascar Rise, oceanic crust shows a crustal thickness averaging 8km thick. In the western part of this margin segment, the crustal thickness mapping suggests that the start of necking may occur onshore rather than offshore compared to further east.

In the central segment, the BH is well defined in Figure 31a and b, and shows a crustal thickness averaging 25km. Crustal thickness contours show that the northern transition from the BH to thin crust (possibly oceanic crust) is sharper than the southern transition. The transfer zones located at the NE and SW ends of the BH are NW-SE orientated based on the contours of the crustal thickness map. However, south of the BH the trends shift to being N-S orientated as the transform zone at the eastern limit of the Limpopo would suggest.

In the west, the MCP in the area of assumed hybrid crust, the crustal thickness is relatively constant averaging 30km and can locally reach 35km. The crustal thickness map (Fig. 3b suggests that the BH connects to the MCP with a slight saddle in between; their join corresponding to the large N-S trending transform zone. South of 22S crustal thickness

shows a sharp transition from ~ 30 km under the MCP to ~ 8km eastwards onto oceanic crust; this transition also corresponding to the N-S transform. Further south this same transform separates crust of thickness up to 20 km under the Mozambique Ridge from thinner ocean crust to the east. The NNV crustal thickness is similar to that of the MCP averaging 30km. Crustal thickness gradually decreases southwards in the NV only reaching values similar to oceanic crust south of 30°S.

The zones interpreted as hybrid crust (i.e., MCP, NNV, and BH) present a quite high but relatively constant crustal thickness averaging between 25Km and 30km.

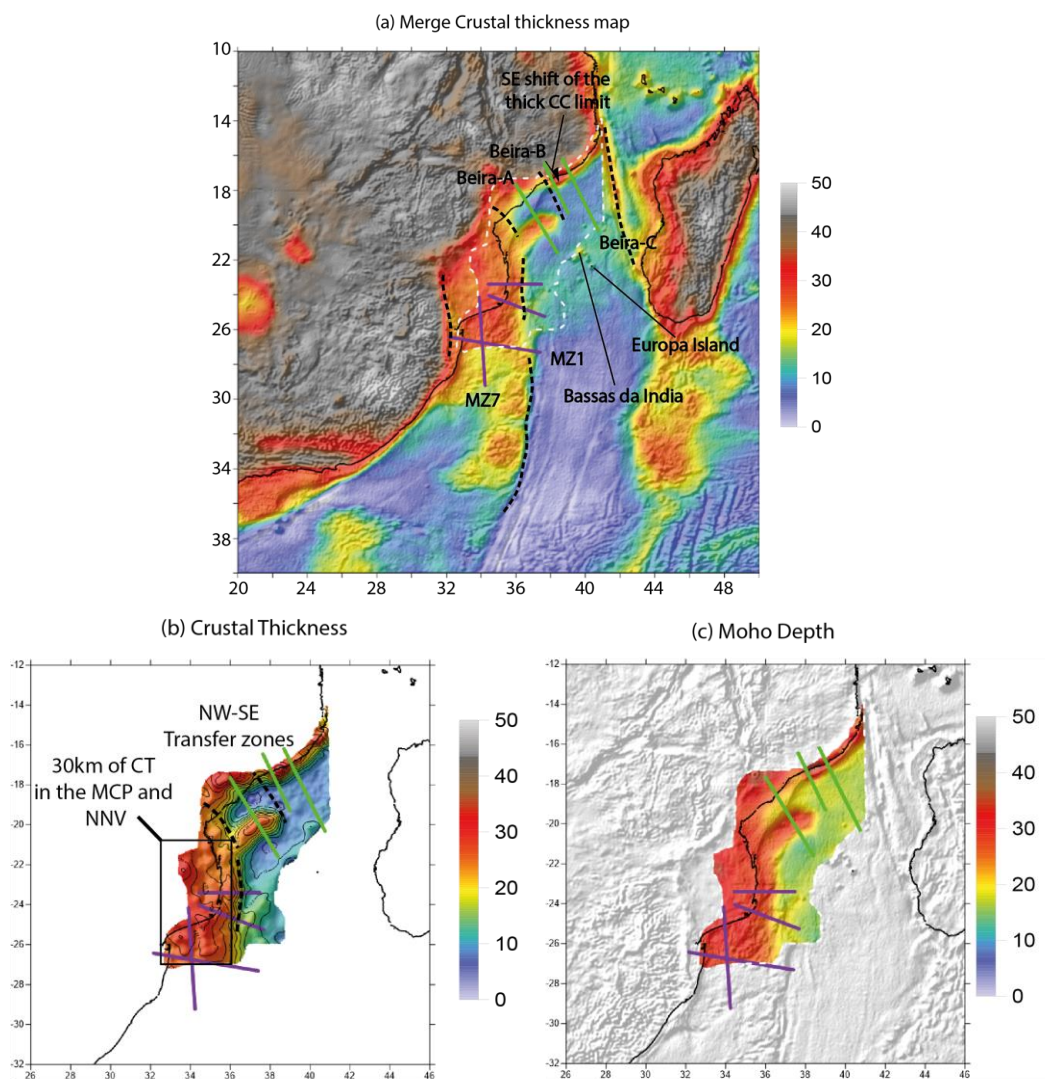


Figure 31: Gravity inversion results using dense 2D seismic reflection data set. White Dashed line represents the area covered by the interpreted dataset. (a) merge of the gravity inversion from the seismic dataset with the gravity inversion from public domain data (b) Crustal thickness results showing the area covered by the seismic dataset. (c) Moho depth results showing the area covered by the seismic dataset.

4.2. Lateral Variations of Basement Density from Gravity Inversion and Seismic Refraction

The lateral variation in basement density, derived by constraining gravity inversion Moho to that obtained from seismic refraction, has been determined for 5 regional profiles; 2 profiles crossing from the MCP onto adjacent marine crust and 3 profiles crossing the Beira High and adjacent Mozambique margin to the east. Refraction seismic Moho depths for the Beira and adjacent margin were taken from (Mueller and Jokat, 2017), those for the MCP and adjacent margin were taken from the IFREMER MOZ campaign. The aim of this analysis was to compare basement density under the MCP and Beira High with that of their adjacent oceanic crust. Crustal cross-sections with their corresponding lateral variation of basement density are shown in Figure 32 and Figure 33.

The crustal cross-sections with Moho from gravity inversion and their corresponding lateral profiles of basement density have been determined using an RMD of both 35 and 32.5 km. The global average of RMD is approximately 37.5 km when a basement density of 2850 kgm⁻² is used in the gravity inversion to determine Moho depth (Cowie et al. 2015). RMD is dependent on mantle dynamic topography, increasing with mantle dynamic subsidence and decreasing with dynamic uplift. Calibration of the distal oceanic Moho from gravity inversion against refraction Moho depth requires RMD values less than the global average consistent with regional dynamic mantle uplift of between 0.5 and 1.0 km (see Cowie et al, 2015 for details of the relationship between RMD and mantle dynamic topography). The RMD value 35 km, suggesting 0.5 km of uplift similar to that predicted by Steinberger et al (2017), provides the best regional calibration; the value of 32.5 km, suggesting 1.0 km of uplift, is required by calibration for lines adjacent to the Miocene volcanic activity of the Europa Islands (Courgeon et al., 2017).

Figure 32 shows crustal cross-sections with Moho from gravity inversion across the BH and further eastwards across the Mozambique margin. Line Beira A calibrates best with an RMD of 35 km while line B calibrates best with 32.5 km. Line C does not calibrate well with either value.

The cross-sections for Beira lines B and C show relatively simple margin structures with Moho depth decreasing from almost 40 km in the continent to normal ocean values

from both the gravity inversion and refraction study. The OCT on line C is wider than on line B. In board the gravity inversion shows Moho

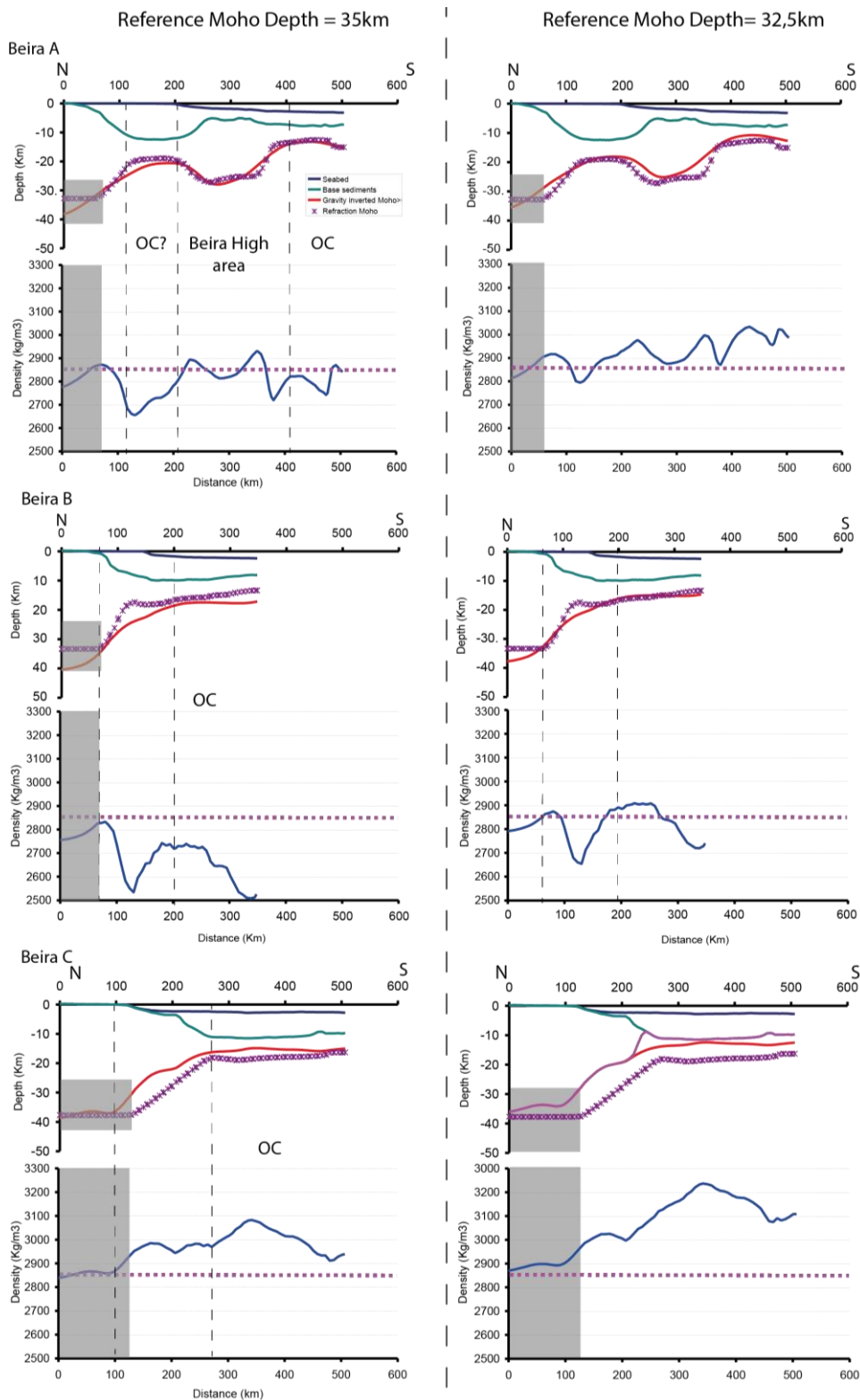


Figure 32: Gravity inversion results using the main interfaces of the refraction data of Mueller et al., 2017. The column on the left shows the results for the model running a 35km Reference Moho Depth (RMD). The column on the right shows the results running a 32.5Km RMD. For each joint inversion, we show the crustal densities need in order to fit the gravity Moho with the Moho interface from the refraction line.

Line Beira A, crossing the BH, shows a much more complex structure with thin crust separating the BH, with crustal thicknesses reaching 20 km, from the continental crust to the north. To the south of the BH crustal thickness are approximately 7 km consistent with ordinary oceanic crust. The thin crust to the north of the BH is of unknown composition. The basement density of the BH is greater than that of the oceanic crust to the south for the gravity inversion with RMD = 35 km. This is not consistent with the BH basement being continental. The refraction Moho in the proximal margin of line A for distance <100 km is extrapolated and cannot be used, however the gravity inversion predicts that the proximal

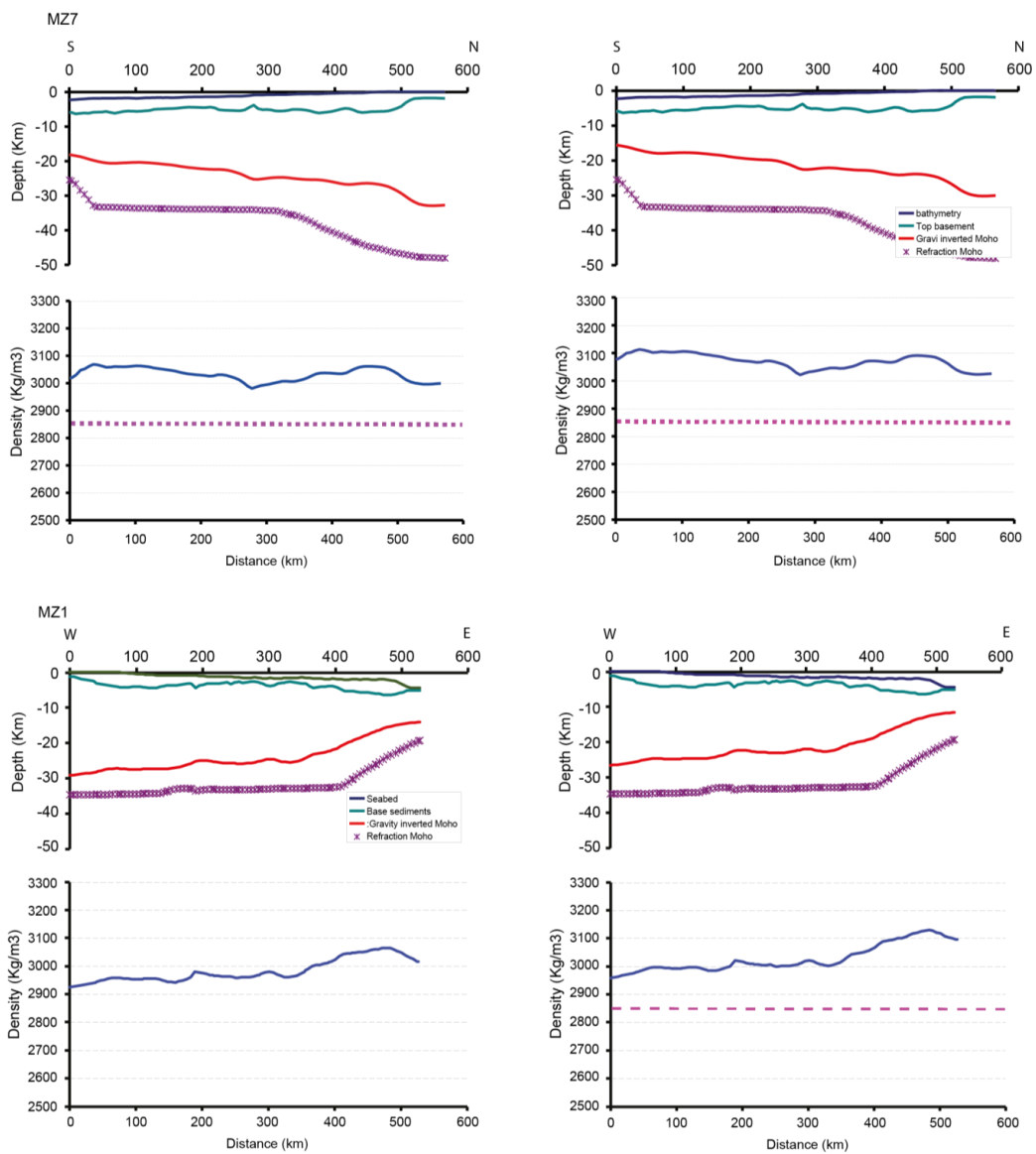


Figure 33: Gravity inversion results using the main interfaces of the refraction data of Moulin et al., 2019. The column on the left shows the results for the model running a 35km Reference Moho Depth (RMD). The column on the right shows the results running a 32.5Km RMD. For each joint inversion, we show the crustal densities need in order to fit the gravity Moho with the Moho interface from the refraction line.

Moho deepens towards 40 km.

Figure 33 shows the crustal cross-sections for the southern On MZ1 and MZ7, the proximal extremities of the refraction seismology are not well constrained (one-way rays only). Neither line reaches oceanic crust which does not allow the calibration of the RMD used in the gravity inversion by comparison with the oceanic refraction Moho. For line MZ7, seismic refraction Moho depths range from almost 50 km in the north in the MCP to 33 km in the south in the NNV. For MZ1, seismic refraction Moho depths average 35 km in the MCP, decreasing to 20 km in the OCT to the east.

For both MZ1 and MZ7 the Moho from gravity inversion using a basement reference density of 2850 kgm^{-3} is substantially shallower than the Moho from refraction seismic. In order to fit the gravity inverted Moho with the refraction Moho, the crustal densities have to be much higher than 2850 kgm^{-3} , with values generally greater than 2950 kgm^{-3} required to reconcile seismic refraction and gravity Moho depths. A similar result is also seen for lines MZ4 and MZ5 which are parallel to line MZ1 but further north.

4.3. Subsidence analysis

The subsidence analysis aims to determine the lithosphere thinning under the MCP during rifting and breakup from the post-rift thermal subsidence of the top volcanics (SDRS). The contribution to subsidence from collapse of mantle plume uplift needs to be also considered. The lithosphere thinning factor is then used to predict the thickness of remaining continental crust under the MCP so that the relative proportions of continental and magmatic crust can be determined for hybrid MCP crust.

We analyse the section presented by Davison and Steel, (2018). The authors calibrated their section using wells (for the Domo-1 location, see Figure 34). The Domo-1 well penetrates volcanics at 2800m depth which are interpreted as the prolongation of the Lebombo SDRs (these SDR are observe and describe in Klausen, (2009)). The drilled SDR are not dated so the oldest age of formation possible is 182Ma (oldest age of the Lebombo extrusive rocks and the youngest possible age is 130Ma (corresponding to the age of the southern Mozambique ridge).

In Figure 34, profiles of water loaded subsidence from flexural backstripping, lithosphere thinning factor and the thickness of residual continental crust are shown. An age

of 150Ma for the Domo-1 volcanics is used. Sensitivity test to using 180Ma and 130Ma are shown in supplementary material). An initial thickness of 37.5km is assumed for continental crust. The sensitivity of the analysis to the collapse of mantle plume uplift is also shown in

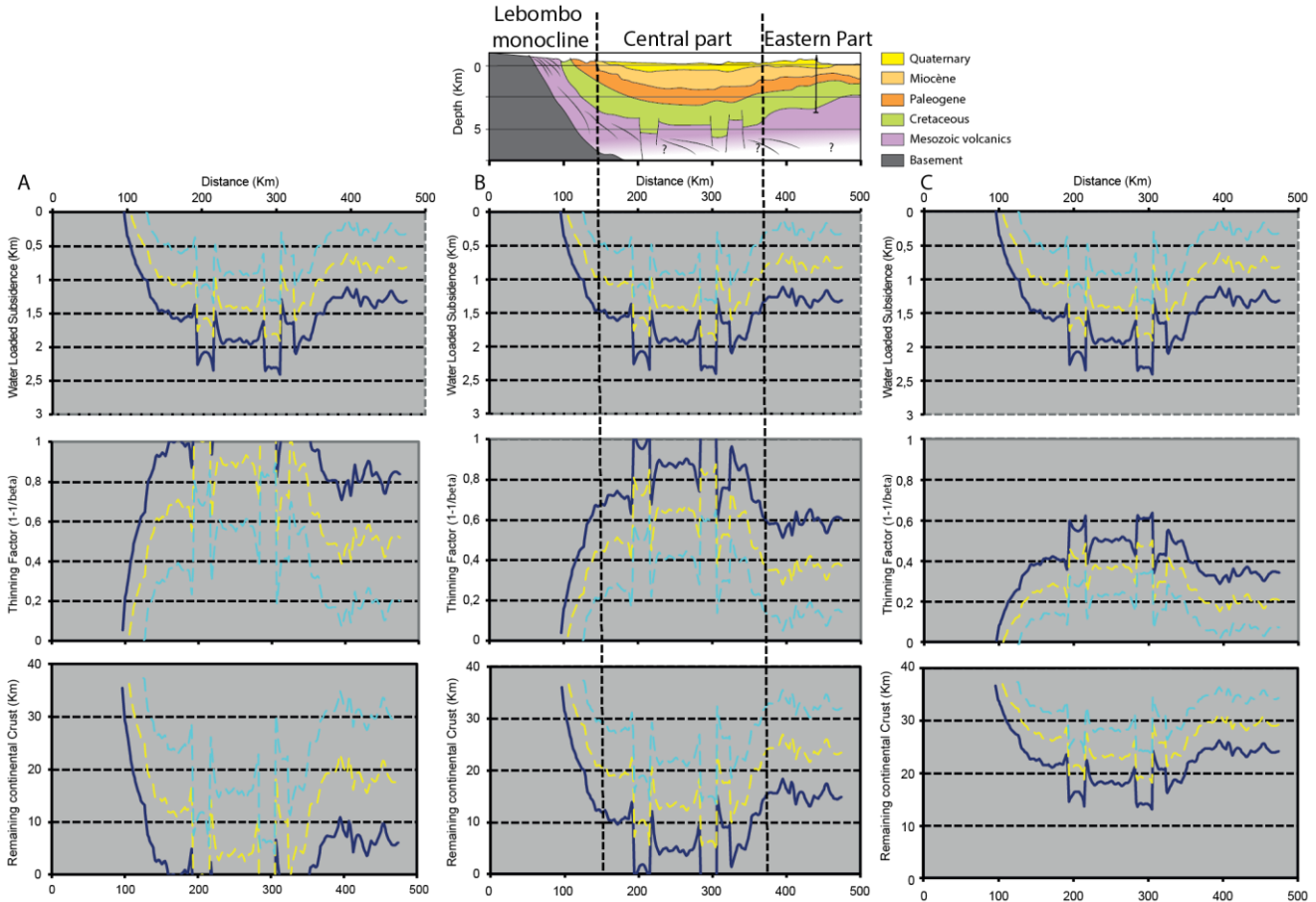


Figure 34: Subsidence analysis of the Mozambique Coastal plains section presented in Davison and Steel, 2018. A) the subsidence analysis is performed using 130Ma for the Central SDR. B) the subsidence analysis is performed using 150Ma for the Central SDR. C) the subsidence analysis is performed using 180Ma for the Central SDR. Dark blue curve represents 0m of dynamic topography at rifting time, Yellow curve represent 500m of dynamic topography, and light blue curve represents 1000m of subsidence. Location of Domo-1 well is also represented on the cross-section above.

Figure 34; the consequences of 0, 0.5 and 1.0 km of plume collapse are examined.

For the case of zero collapse of mantle plume uplift, the water loaded subsidence (Figure 34) increases eastwards from the Lebombo Monocline area from 0km to 1.5km, to 1.7km in the deepest part of the MCP and 2.2 km in the Cretaceous grabens. On the eastern flank water loaded subsidence decreases to 1.2 km. The corresponding thinning factors reach a maximum value of 0.7 to 0.9 in the centre of the MCP excluding the Cretaceous rifts. The effect of including mantle plume uplift collapse is to decrease the water loaded

subsidence and also decrease the thinning factor. This sensitivity for uplift collapse of 0.5 and 1.0 km is also shown in Figure 34.

For the case of no mantle plume uplift collapse, the thickness of the remaining (residual) continental crust thickness in the centre of the MCP is between 5 and 10 km, increasing to both eastern and western flanks. If 0.5 or 1.0 km of uplift collapse is assumed then the thickness of the remaining continental crust increases to approximately 15 and 25 km respectively.

5. Discussion

5.1. The implications of the geophysical and geodynamic analyses

I use the results of the geophysical and geodynamic analysis to test the hypothesis that the Mozambique Coastal Plains and the Beira High are underlain by hybrid crust consisting of thinned continental crust and large quantities of magmatic material. Such hybrid crust is expected to have the following characteristics: a relatively smooth, unfaulted top basement; approximately parallel top basement and Moho; a basement density greater than that of continental crust; and post-rift subsidence consistent with the amount of remaining continental basement.

Both the gravity inversion and the refraction seismology show a similar crustal thickness pattern for the Beira High with thin crust to the north separating it from the African continent and with thin crust to the south with thicknesses consistent with oceanic crust (Figure 32). Basement density of the Beira High determined by matching the gravity inversion Moho with that from seismic refraction is greater or equal to that of the oceanic crust to the south, rather than less. These densities suggest that the Beira High is not predominantly made of continental material. The basement density pattern across the Beira High shows two peaks of higher density ($>2900\text{Kg/m}^3$) at its edges which could indicate greater magmatic content there compared with magmatically intruded continental crust in the centre of the block. This statement is in agreement with the high seismic velocities shown in the lower crust in the refraction cross-sections of Mueller et al., 2017. Comparing the crustal basement densities of the Beira High with that under the Mozambique Coastal Plains suggest that the Beira High may constrain a lower proportion of magmatic addition and a larger proportion of continental material resulting in its slightly lower basement density. The difference in the distance to the supposed magmatic source (or mantle plume)

or the separation by a transform zone (Limpopo transform zone) might be responsible for the lower amounts of magmatic addition to the Beira High.

In the Mozambique Coastal Plain and Northern Natal Valley, top basement interpreted from seismic reflection data is believed to be the top of volcanic SDR like wedges. Those wedges fill up the available accommodation space and show high amplitude reflections (see Tomasi et al., subm) interpreted as the top of mainly magmatic material with erosion surfaces. The top of those wedges is generally flat resulting in a large area (<10000Km²) of relatively constant crustal thickness of approximately 25km when determined by gravity inversion (Figure 31 and Figure 32). Seismic refraction gives a crustal thickness between 5 and 10 km greater. Moho depths from seismic refraction are deeper than might be expected from isostasy although their accuracy is uncertain; the refraction lines were not everywhere reversed. If the refraction Moho depths are taken at face-value, reconciliation of the Moho depths determined by gravity inversion and seismic refraction requires a high basement density, between 2900 and 3050 kgm⁻³, under the MCP and NNV. Such high densities are not consistent with continental basement. They are also higher than that of normal oceanic crust. These high densities could be explained by decompression melting related to a mantle plume leading to crystallization of picritic material. Such types of magma form in a low pressure and high temperature context which is compatible with a mantle plume environment and is observed in the field (Bristow, 1980). On MZ1 we observed the general eastward increase of the densities which might account for the decreasing impact of continental crust and the higher impact of magmatism especially as it is closer to the northern part of the Mozambique Ridge. I also measure lithosphere thinning factors from post-rift thermal subsidence which for the Mozambique Coastal Plains. This shows that the remaining continental crust is low in the central part of the Mozambique Coastal Plains, with values 20 km or less, but increases on the flanks.

5.2. Implications for the Mozambique Channel opening

The geophysical and geodynamic approaches used in this study provide arguments to verify the proposal by Tomasi et al. subm, that the Mozambique Coastal Plains was formed by stretching and thinning of continental crust during the separation of Antarctica and Africa. In the Jurassic, and that simultaneously, magmatism (extrusive and

intrusive/underplating) compensated continental crustal thinning by thickening the crust and filling the accommodation space. (Moulin et al., 2019) compared the seismic velocity depth profiles in the NNV with those in the neighbouring cratons at the time of extension (i.e. Kaapval Craton in Africa and Grunnehogna Craton in Antarctica,) (see Figure 35). Seismic velocities for the MCP seem to be higher than those of the cratons which might be explained by magmatic additions. However, they also observe that the 1D seismic velocity depth profile for the MCP are different from those of oceanic plateaus around the world, showing lower velocities, which is consistent with the presence of some continental crust (Figure 35b).

The results of the subsidence analysis are dependent on the magnitude of the mantle dynamic uplift related to the Karoo plume (*stricto senso* these results depend on the magnitude of the collapse of dynamic uplift). Depending on the magnitude of uplift collapse, the subsidence analysis implies a thickness of remnant continental crust in the MCP of between 5 (for zero collapse) and 20 km (for 1 km collapse). This is compatible with the observed refraction seismology results showing 40km of overall crustal thickness (continental crust + magmatic addition). 20 km of remaining continental crust, corresponding to 1 km of mantle plume collapse, is similar to that estimated by Tomasi et al., *subm* using other arguments. The subsidence measured in this work is less than that interpreted by Davison and Steel, (2018), but in this study, we show the water loaded subsidence; sediment loaded subsidence gives higher values than water loaded subsidence (Cardoso and Hamza, 2014; Cowie et al., 2015).

5.3. Some generalities for the investigation of hybrid crust

These results of this work have implications for other mantle plume related rift systems where magmatism masks the nature of the crust. For instance, recent studies proposed that Iceland is formed of highly thinned continental crust thickened by volcanics and magmatic addition (Foulger et al., 2019). In contrast to the area investigated in our study, Iceland is still thermally supported and is subaerial. Hybrid crust, consisting of thinned continental crust and large quantities of magmatic addition, should be characterized by a magmatic relatively unfaulted flat topped basement, possibly with SDRs. If the top of the hybrid basement shows evidence of subaerial exposure, then the accommodation space

responsible for the deposition of overlying sediments is generated by a combination of post-rift thermal subsidence and mantle plume uplift.

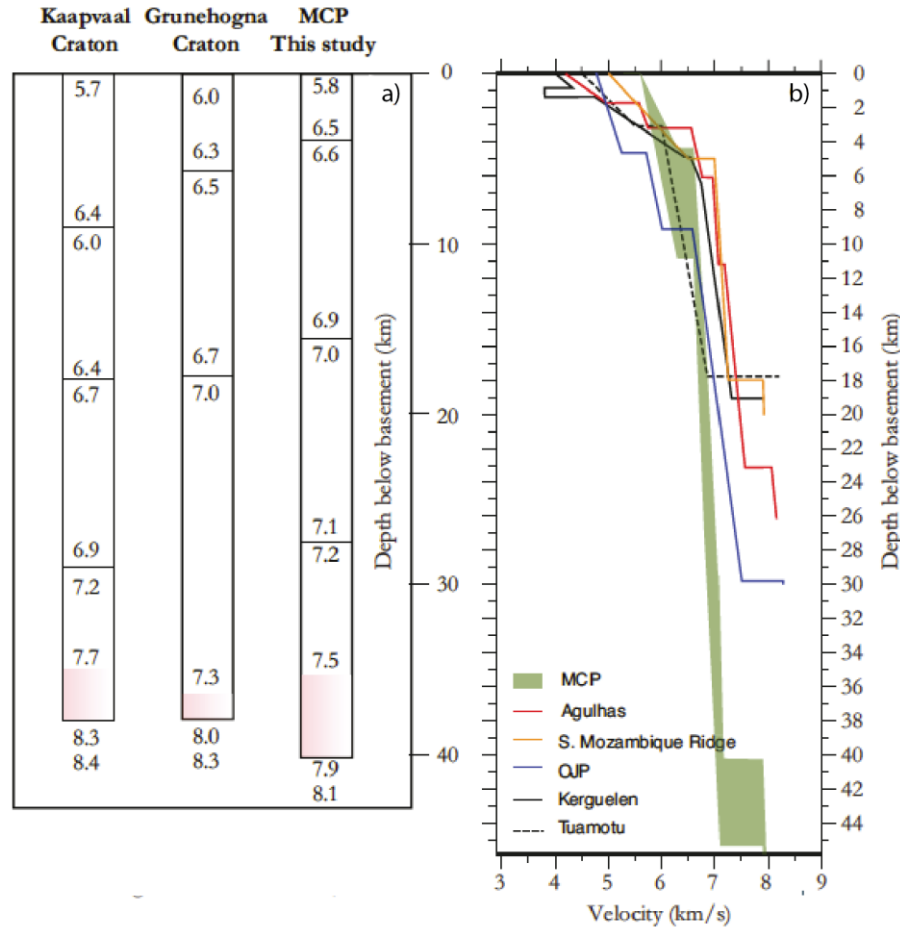


Figure 35: a) Comparison of crustal thickness between the MCP and cratons after Moulin et al., (2019): the Kaapvaal Craton in Africa, after (Nguuri et al., 2001; Kwadiba et al., 2003) and the Grunehogna Craton in Antarctica (Hubscher et al., 1996); (b) 1D velocity-depth profiles of the MZ7-MCP profile (in green) compared to oceanic plateaus: Agulhas plateau (Gohl and Uenzelmann-Neben, 2001), the South Mozambique Ridge (Gohl et al., 2011) the Ontong Java Plateau (Miura et al., 2004), the Kerguelen plateau (Charvis and Operto, 1999) and the Tuamotu plateau (Patriat et al., 2002).

By using gravity inversion mapping of crustal thickness, comparison of Moho depths from gravity inversion and seismic refraction to determine basement density, and subsidence analysis to determine lithosphere thinning, we can greatly supplement the information gained from seismic reflection data alone. In particular a diagnostic characteristic of hybrid crust is its high basement density which can be determined by the

combination of gravity and seismic geophysical methods. High density crust can be associated with mafic material (Hacker et al., 2015, Table 2) which provides evidence for a high proportion of magmatic addition formed by decompression melting in a mantle plume context.

6. Conclusion

It remains difficult to characterize hybrid crust such as that underlying the MCP by using only geological approaches. Tomasi et al., *subm.* demonstrate that using classic seismic interpretation is unable to identify rifted margin hybrid crust and then restore them. Such hybrid crust should present certain characteristics; a relatively smooth unfaulted top basement; top basement approximately sub-parallel to the Moho; possible SDRs; possible subaerial emergence and erosion of top basement; basement density higher than normal continental crust; a particular post-rift thermal subsidence pattern. We determine these characteristics for the Mozambique Coastal Plains using quantitative geophysical and geodynamic analyses to supplement seismic interpretation. The determined characteristics suggest that the Mozambique Coastal Plains are underlain by hybrid crust consisting of remnant thinned continental crust and large amounts of magmatic additions. The thickness of the magmatic addition is at least equal to but probably exceeds the thickness of remnant continental crust. Using these quantitative geophysical and geodynamic methods we also establish a work-flow which can be applied globally to examine other hybrid crust examples.

In the case of the Mozambique Coastal Plains, we propose on the basis of the measured high crustal density that the magmatism is picritic. Such an interpretation is in agreement with a mantle plume rift environment and with the observation of field geology. The Beira High, while showing basement densities more comparable with oceanic values rather than continental, does not show the same high densities as seen under the MCP. This lower basement density of the Beira High compared with the MCP may imply either that the magmatism there is less picritic or that the proportion of magmatism mixed with remnant continental crust is lower. Either of these interpretations would be consistent with the Beira High being further away from the mantle plume than the MCP, and separated from it by a transform.

In summary the hybrid crust of the MCP is characterized by thick high-density crust with magmatic addition equal to or exceeding the thickness of remaining thinned

continental crust, a relatively flat unfaulted top basement formed by volcanic flows filling accommodation space and massive intrusions. Post-rift thermal subsidence is large but less than that of oceanic lithosphere but is supplemented by mantle plume uplift collapse, together generating significant accommodation space for sedimentation.

This study brings some constraints to the processes responsible for hybrid crust formation in a rift context, however their detailed architecture still remains unclear.

In the third chapter, I highlight key characteristics of hybrid crust (magmatic-continental crust) and confirm that the Mozambique Coastal Plains and the Beira High do correspond to this type of crust. Hybrid crust are form when the crust is thinned during extension and syn-tectonic magmatism is filling the created accommodation space. This study leads to the importance of assessing the timing of the magmatic production as well as its budget during the evolution of the rift which is developed in the chapter IV.

**Chapter IV: A New Approach
to Characterize Rifted
Margins: Linking Crustal
Shapes with Magmatic Timing
and Budgets**

A New Approach to Characterize Rifted Margins: Linking Crustal Shapes with Magmatic Timing and Budgets

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1. Introduction:

The binary magma-rich vs magma-poor classification of rifted margins has been introduced to distinguish between margins showing different magmatic budgets and structures, in particular the presence or absence of Seaward Dipping Reflection (SDR) sequences (Eldholm et al., 1989; Planke and Eldholm, 1994; Geoffroy, 2001; Reston, 2009; Franke, 2013; Gillard et al., 2015). This classification does, however, neither consider the relative timing of lithospheric vs. crustal thinning, nor the crustal shape of rifted margins, both of which are first order characteristics of rifted margins. Thus, rifted margin classification should not only be based on how much magma formed, but need also to include when and where magma formed with respect to the thinning of the continental crust and lithosphere.

Although many studies have led to major progress in understanding when, where and how extrusive magmatic systems emplaced during rifting, little is known about how much corresponding magma remains in or at the base of the new magmatic crust and when the magma is emplaced relative to the thinning of the crust (Lizarralde et al., 2004; Quick et al., 2009). The aim of this study is to provide a simple new classification of rifted margins in which the crustal shape, relative timing and budget of magma emplacement represent first order parameters to describe rifted margins. The first order crustal shape of rifted margins

can be directly observed with high quality, depth-converted long offset reflection seismic sections. However, both magmatic budget and relative timing of magma emplacement with respect to continental crust and lithosphere thinning are very difficult to determine based on seismic interpretation only. A first difficulty is to obtain relative and absolute time constraints on magmatic systems. Another difficulty is to determine the budget of magmatic additions, in particular for the intrusive, often called underplated, magmatic components. Igneous rocks show velocities and densities that are often indistinguishable from those of thinned continental crust resulting in uncertainty in magmatic addition volume estimates (Peron-Pinvidic et al., 2016). There is, however, an intrinsic link between shape of the crust in the ocean-continent transition and magmatic budget and the timing of first magma-production with respect to crustal and lithospheric thinning. At present, there is no numerical dynamic model of rifted continental margin formation that can satisfactorily integrate magma-production and quantify in an accurate way the timing and budget of such magmatic systems linked to the formation of rifted margins. Therefore, and because we lack a good stratigraphic framework to define the time-space evolution of rift systems at most margins, the definition of magmatic budgets and relative timing of magma emplacement remains challenging and yet unconstrained.

In this study, we propose a simple approach that enables us to compare end-members relative to what we define as a “standard” rifted margin by using a combined observation-modelling approach. High quality, long offset seismic sections enable the observation of the first order characteristics of margins which are: 1) the shape of the crust delimited by top basement and Moho, 2) the nature of transition to first oceanic crust that corresponds either to a step up or step down onto the steady state oceanic crust, and 3) the morphology of the top basement that can be either fault or magma controlled. These in turn can be compared to first order kinematic model results in which simple margin architectures including magmatic additions can be generated by varying only two parameters, namely the relative timing and the budget of a magmatic system.

2. First order characteristics of rifted margins

Magma-rich margins are defined as margins with an elevated magmatic budget, heavily intruded continental crust and overlain by extrusive and intrusive magmatic flows and underplates (Geoffroy, 2005; Franke, 2013). The magmatic additions are interpreted as syn-

tectonic, associated with lithospheric breakup. On seismic data, first order characteristics of such margins are Seaward Deeping Reflectors (SDR) with a smooth and little structured top basement. Top basement and Moho converge oceanward and first oceanic crust occurs at the inflexion point where top and base crust become parallel, typically $2s/6,5 \pm 1\text{km}$ thick. Although this latter statement might be argued as magma-rich margins models usually show thicker oceanic crust, the observation shows often normal crustal thickness or thinner. Thus, these margins show a characteristic shape and a top basement that steps down onto oceanic crust.

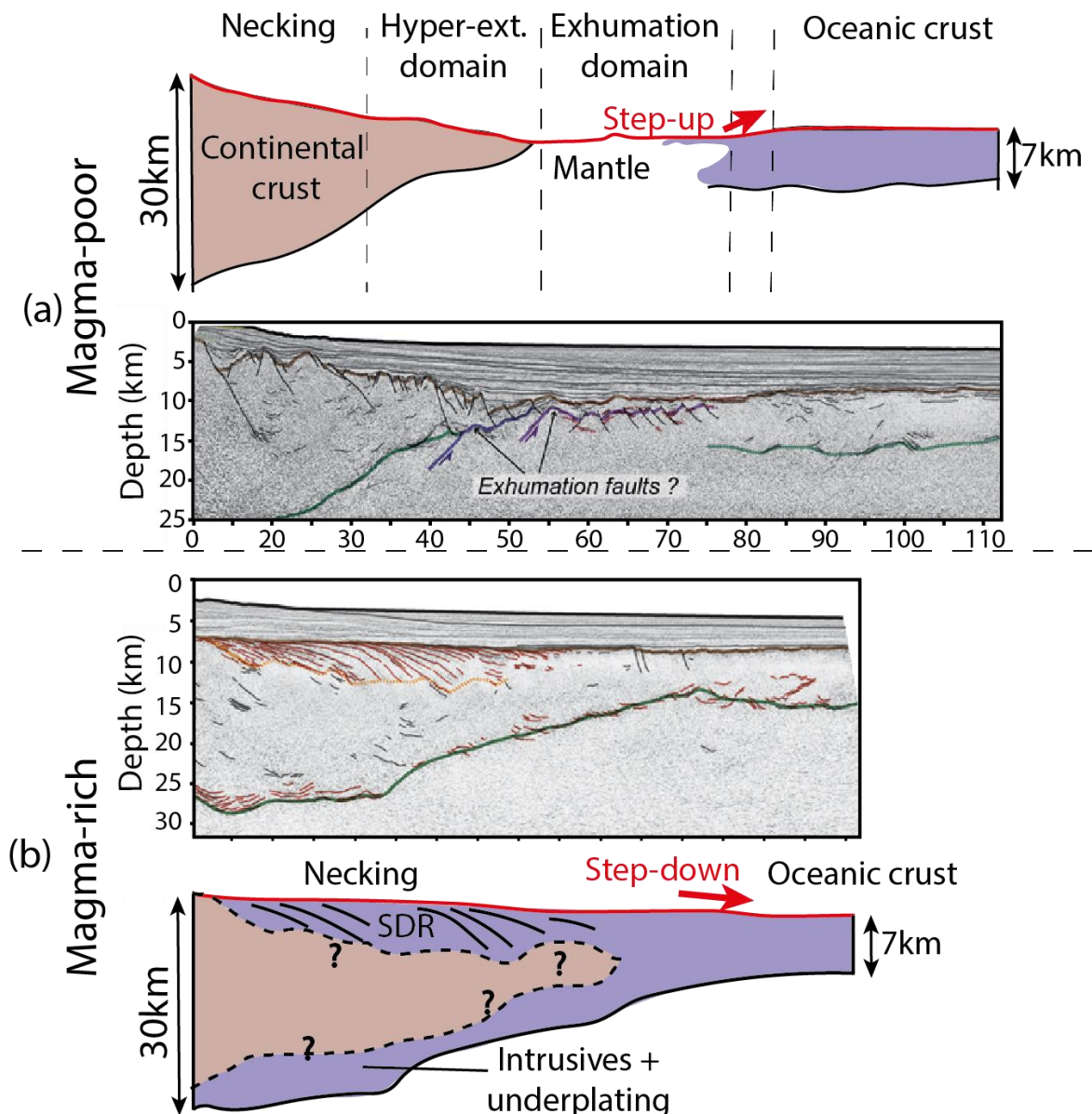


Figure 36: Highlighting the differences between magma rich and magma poor margins. B) Interpretation of the Uruguayan rifted margins. A) Interpretation of the South Indian Rifted Margins. Interpretations made on ION PSDM line from Tugend et al., 2018.

Magma-poor margins are defined by a low magmatic budget and a variable crustal structure including, from proximal to distal, four domains: 1) a strongly structured, fault bounded top basement with parallel top and base crust, 2) a variably width necking zone where a combination of brittle and ductile processes thin the crust to less than 10km (Mohn, et al 2012, Chenin et al. 2019), 3) a wedging, asymmetric hyper-extended domain with both high- and low-angle extensional faults (Nirrengarten et al., 2018), and 4) an exhumed mantle domain, showing top basement at $10\pm 1s$ and no Moho reflectivity. Magmatic processes become only evident some distance after the crust has been thinned to zero, indicating that crustal thinning and magmatic additions are separated in time and space (Gillard et al. 2019). On seismic data, first order characteristics are: 1) a wedging of the crust with variable angles of convergence of the top basement and the Moho, and 2) more than three inflexion points drawn by the outline of the top-basement, 3) a structured top basement, and 4) a stepping up of the top basement outline onto oceanic crust.

Thus, at a first order, margins can be characterized by their shapes, inception points and the stepping up or down onto oceanic crust (Figure 36). We define initial, pre-rift crust where top and base crust are parallel and 35 ± 5 km thick, and the material constituting the crust is inherited. Steady state, Penrose oceanic crust is defined as crust where top and base are parallel, 6.5 ± 1 km thick, and made fully of new igneous material. The domain in between these two well defined types of crust is made by crust that is characterized by converging top and base crust, include inflexion points and sometimes bulges, often also referred to as “outer highs”. Two main characteristics can be defined in these transitional domains: 1) smooth vs structured top basement, and 2) a stepping down or up onto ocean crust. We use these first order observables together with a simple modelling approach to discuss the main two parameters that may control the architecture and evolution of rift systems leading to lithospheric breakup.

3. Model

At present, no dynamic model can predict syn-tectonic magma in a realistic way. While the physics of decompression melting during lithosphere stretching and thinning is well understood, great uncertainty exists in the initial conditions required by modeling.

These initial condition uncertainties include the inherited mantle composition and chemistry of source material and whether it is depleted or enriched, initial asthenosphere temperature and the possible presence of hot spots, initial lithosphere temperature which depends on crustal thickness, composition and inheritance, rifting rates, and the mode of lithosphere rift deformation. In this study, we use a simple kinematic model to generate an isostatically balanced thermally equilibrated rifted continental margins to which magma has been added. In the model, the distribution of tectonic thinning and the location and magnitude of magmatic addition are independently defined. The model is simple and does attempt to directly relate melt generation with tectonic thinning. The model generates a cross-section showing bathymetry, the thicknesses of extrusive magmatism, residual thinned continental crust and intrusive magmatism represented as underplate, and Moho (see Figure 37). The parameters controlling the distribution of thinning and the quantity of magmatic addition are summarized in the annexes.

We use the kinematic model to investigate how the timing (when) and quantity (how much) of magma production during extension controls the first order shape of the margin. Our “standard” rifted margin model uses a parameterization (Chappell & Kusznir 2008) of the decompression melt model of White & McKenzie (1989) with melt initiation starting at a thinning factor of approximately 0.7 and producing a maximum melt thickness of 6.5 ± 1 km, corresponding to the average thickness of oceanic crust (Dick et al. 2003). Our model assumes that generated magma is distributed with 37% as extrusive and 63% as underplates. The stretching and thinning of continental crust and lithosphere are assumed to be depth uniform consistent with the model of McKenzie (1978). In order to investigate the relative interplay of tectonics and magma generation we vary two parameters. The first parameter is the relative timing of the start of magmatism compared to the “standard” margin. We introduce an advance or delay in the onset of melt generation with respect to the “standard” model. The second parameter is the relative volume of magmatic production compared to the “standard” model.

4. Results

The crustal cross-section, isostatically balanced and thermally re-equilibrated, predicted for our “standard” model (Time normal-Budget normal; Tn-Bn) is shown in the

central panel of Figure 37. For the thinning parameters used in this particular model, decompression melt initiates at a distance of 110 km, when continental has been thinned to 10.5 km thick. Onset of seafloor spreading happens when top and base crust are parallel, 6.5km thick and crust is made by igneous material only. In the “standard” model, the crustal shape within the OCT is controlled by the superposition of residual inherited continental crust and the newly formed igneous crust. Three inflection points can be defined, the first defines the onset of crustal thinning (necking), the second corresponds to onset of magma-production, and the last to the onset of steady state seafloor spreading defined as lithospheric breakup. The two major observations can be made: 1) crustal thinning and magma emplacement coincide in space (and time), and 2) top basement is stepping down onto oceanic crust.

On Figure 2, the left to right panel variation is determined by the variation of the timing of magmatism arrival. The left column represents anticipated arrival (an offset of -100km has been generated) and the right column represents a delayed magmatism arrival (offset of 150km). The top to bottom panel variation is determined by the increase of the magmatic budget from 0km of magmatic thickness (top row) to 35km of magmatic thickness (bottom row).

Considering the end-member magma-poor and magma-rich margins, two characteristics can be found. In all models with a delay in the start of decompression melting with respect to thinning (Time-delay model; Td, left panel in Figure 37), the crust wedges to zero and top basement is stepping up onto oceanic crust. In the models with a high magmatic Budget (Bh), a bathymetric bulge (high) can be found. In these cases where magma is delayed, the bulge is composed only of newly created igneous crust and the culmination occurs oceanward of the termination of the continental crust.

The position of the bulge relative to the termination of continental crust depends of the timing of decompression melt initiation with respect to thinning. In a Time-Normal model (Tn) where decompression melting is in step with thinning, the axis of the bulge coincides with the termination of the continental crust. Where decompression melting is early with respect to thinning (Time-advanced model; Ta), the bulge occurs on continental crust. The amplitude of the bathymetric bulge increases with the volume of melt.

In the case of a very high magmatic budget (Ta-Bh), the combined thickness of continental crust and magmatic addition could become very large (> 50km in model Ta-Bh). However, such a situation may not be realistic, as discussed below. This leads to the question if all examples can be observed. Another question relates to what processes can explain excess magma or retardation of magma.

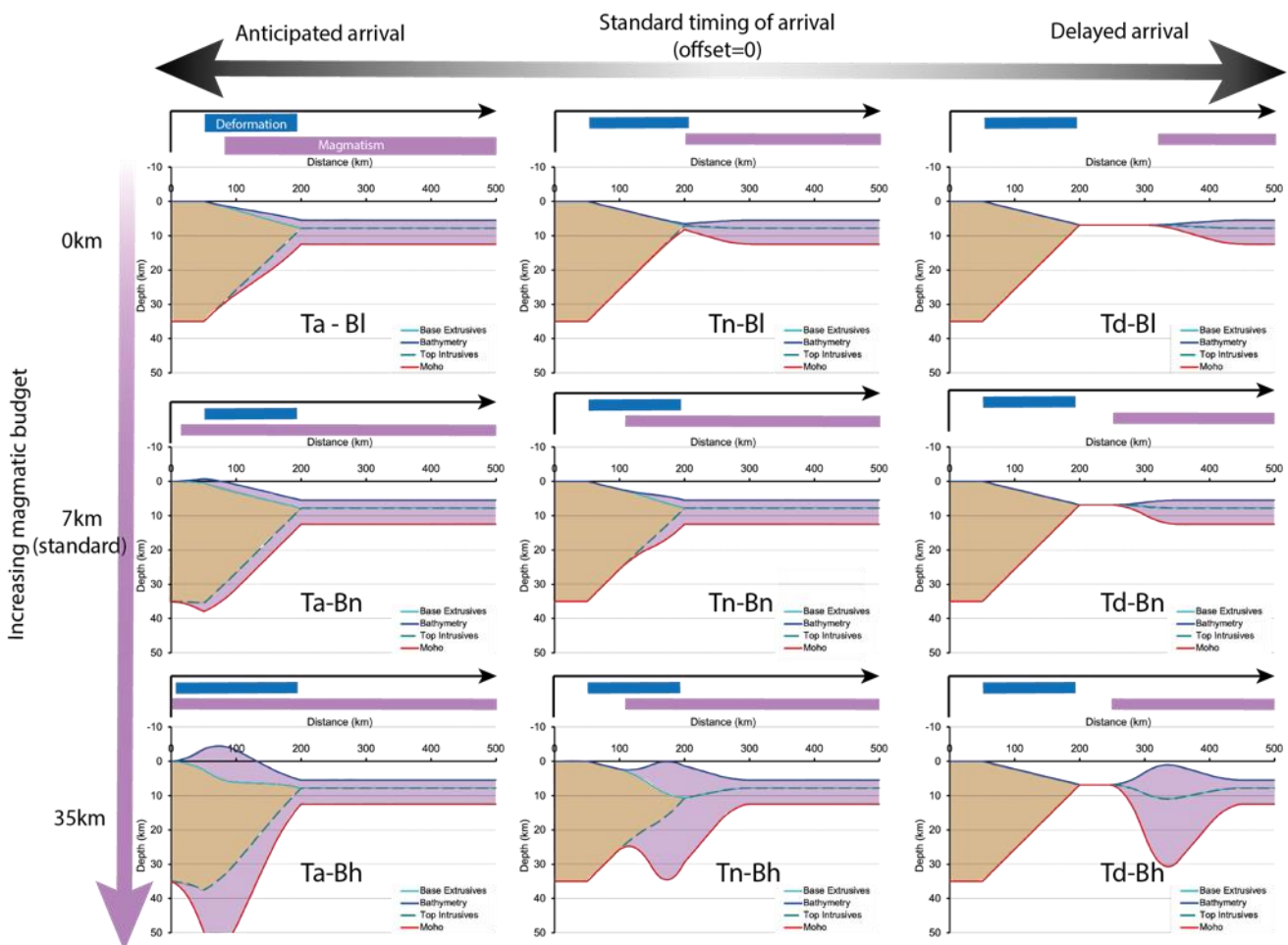


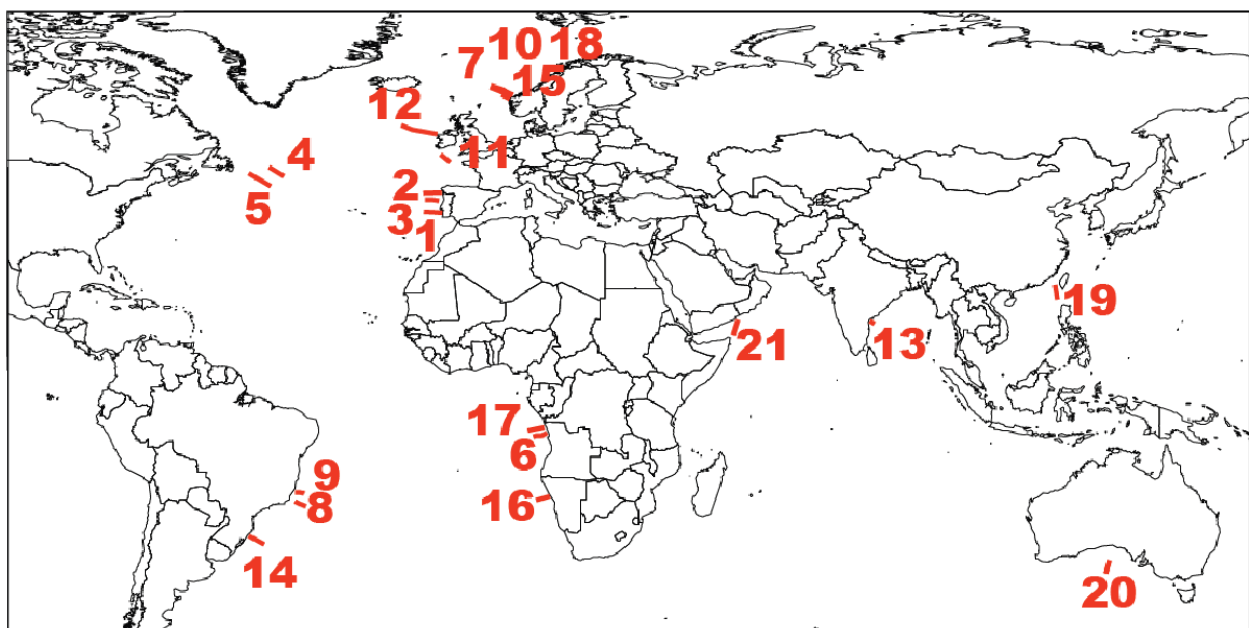
Figure 37: Resulted Thermally equilibrated margins from the model. Top horizontal axis represents the relative timing of arrival of magmatism compared to standard. Vertical axis represents the magmatic budget and initial thickness of decompression melting. The brown color represents continental crust and purple represents magmatic addition. The diagrams on top of each margins shows the relative position of magmatic processes (purple) compared to the thinning of the crust (blue).

5. Discussion:

5.1. Model vs. Analogues

The Figure 38 presents examples of margins around the world and an associated study which allow us to categorize each example according to the new classification that we propose in this study (after . We also present

The results of our simple model show that the variation in two parameters (relative timing of magmatism, and amount of magmatism) shows a wide range of OCT shapes. Taking into account the relative timing of magma emplacement is important. In our “standard” margin, magma production initiates when the crust is 10.5km thin. The total crustal thickness (inherited plus new igneous crust) thins to 6.5 ± 1 km and is characterized by a down-stepping onto oceanic crust. This suggests that the continental crust continues thinning after the onset of magma-production and that crustal thinning (CT) is higher than magma-thickening (MT). Indeed, if the top basement and the Moho are not parallel, this testifies for a disequilibrium between (CT) and (MT). When top basement and Moho are parallel, it means either that Thus, in our “standard” model, the magma is syn-tectonic and the ratio CT/MT is >1 . Such “standard/normal” margins may show SDR or other types of syn-tectonic, likely sub-aquatic magmatic additions. In such margins, crustal thinning and magma-production are coupled and the edge of continental crust corresponds to onset of seafloor spreading and is defined by an inflection point.



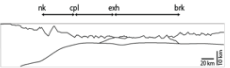
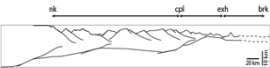
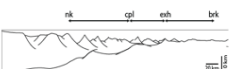
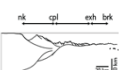
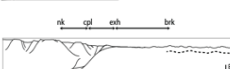
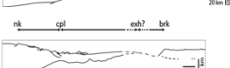

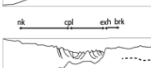
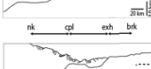

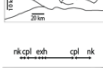
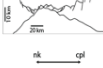

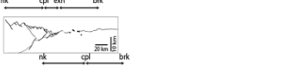
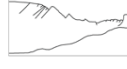
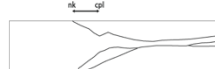

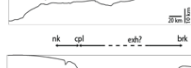

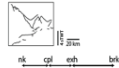
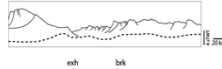
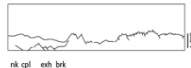

Section		Classifications
1 IAM5 (Afilhado et al., 2008)		Td-Bn
2 ISE1 (Sutra et al., 2013)		Td-BI
3 TGS+LG12 (Sutra et al., 2013)		Td-BI
4 SCREECH1 (Sutra et al., 2013)		Td-BI
5 SCREECH2 (Sutra et al., 2013)		Td-BI
6 Angola (Unternehr et al., 2010)		Td-Bn
7 Norway (TrII Nirrengarten et al., 2014)		Td-Bh
8 Campos Basin (Zalán et al., 2012)		Td-BI
9 Esperito Santo Basin (Zalán et al., 2012)		Td-BI
10 Norway (Osmundsen and Ebbing, 2008)		Td-Bn
11 E-Porcupine (McDermott et al., 2014)		Td-BI
11 W-Porcupine (McDermott et al., 2014)		Td-BI
12 E-Rockall (Welford et al., 2010)		
12 W-Rockall (Welford et al., 2010)		
13 India (Radhakrishna et al., 2012)		Td-BI
14 S-Pelotas (Stica et al., 2014)		Ta-Bh
15 Norway (Kvarven, 2013)		T
16 Namibia (Gladzenko et al., 1998)		Ta-Bh
17 Angola (Aslanian et al., 2009)		Td-Bn
18 Norway (Osmundsen and Ebbing, 2008)		Td-BI
19 China Sea (Lester et al., 2014)		Td-Bn
20 South Australia (Direen et al., 2008)		Td-Bn
21 Aden (Leroy et al., 2010)		Td-Bn

Figure 38: Map of the World margin examples and their classifications according to the shape of the crust and the induced magmatic timing and magmatic budget. The table below shows the sections presents the outline of the Moho and top-basement, after Chenin et al. (2017).

In cases where magma-arrival is delayed relative to the “standard” model, crustal thinning and onset of magma are separated in time but also in space and as a consequence, mantle exhumation can occur. In these margins, magma emplacement is late, postdates crustal thinning and occurs most likely below sea-level in sub-aquatic environments. Thus, in such systems sub-areal SDRs are unlikely to form, top basement is usually rugose and a step up onto oceanic crust is expected. In such margins hyperextended and exhumed mantle domains can be identified (Gillard et al., 2015, 2016; Peron-Pinvidic and Osmundsen, 2016). Examples of such margins are the Iberia margin (LG12, SCREECH1, SCREECH2 in Sutra et al., 2013).

When magma arrival is in advance of crustal and lithosphere thinning and the magmatic budget is high (Ta-Bh), magmatic thickening (MT, i.e., the thickness generated by the addition of extrusive and intrusive magmatism) can compensate crustal thinning (CT, i.e., the amount of accommodation space created by crustal thinning) ($CT = MT$). In such a case the total crustal thickness does not decrease however crustal composition, lithosphere thermal state and subsidence history differ from that of normal continental crust. Also, while magma emplacement coincides with crustal thinning it is typically subaerial. If CT equals MT (i.e. that the magmatic additions compensate the crustal thinning in order to maintain the total crustal thickness constant), the proportion of new igneous material relative to inherited continental crust increases gradually, but in practical it is difficult to determine the crustal structure of such domains. Examples of such margins are the Mozambique /Limpopo system (Tomasi et al. *subm*), Afar (Stab et al., 2016), Jan Mayen (Blischke et al., 2017), or the Sao Paulo plateau (Otávio Gomes et al., 2013). Interpretation of these systems remains debated, since geophysical data alone cannot discriminate between new igneous crust and inherited continental crust. Such systems are difficult to image and the crust remains thick resulting in ongoing debates about the nature of these “plateaus”, as illustrated by conflicting kinematic restorations or atypical subsidence histories.

5.2. Parameters translating Processes

For the “standard” model, magma production corresponds to decompression melting of a standard mantle using a depth-uniform lithosphere stretching and thinning model

(McKenzie 1978). Magma budget (and composition) depend on the melt parametrization e.g. White & McKenzie (1989). In the “standard” model, the notion of lithospheric inheritance (depleted or enriched) is neither required nor suggested. The overall magmatic budget of these margins should not exceed $6,5 \pm 1$ km. In examples where magmatism occurs early at an incipient stage of extension, first magma production cannot be solely explained by lithosphere extension and depth-uniform rifting is unable to predict magma production without crustal/lithospheric thinning. To explain anticipated magmatic activity linked to the formation of Large Igneous Provinces (LIP) a common model is that of hot- or wet-spots including the existence of very fertile mantle and/or elevated mantle temperatures (White and McKenzie, 1989; Skogseid et al., 2000; Tugend et al., 2018). In such situations excess magma production seems not to be directly related to extension. However, the coincidence of magmatic and extensional systems can account for the occurrence of thick magmatic sequences as the creation of accommodation space by extension can be directly filled up to space by magmatic additions.

In contrast, in rift systems where magma generation appears to lag behind lithosphere stretching and thinning, mantle rocks can be exhumed, an observation that cannot be explained with the “standard” depth uniform rift model. In such systems, The retardation of magmatic arrival can be explained either by slow extension rates, cold mantle temperatures (White and McKenzie, 1989), or the occurrence of inherited, depleted mantle (Müntener et al. 2004). More recent studies on the Iberia-Newfoundland margins show that the combination of supra-subduction mantle and depleted mantle related to late or post-orogenic collapse can explain mantle exhumation (Chenin et al., 2015). Thus, while magma-rich margins seem to be related to plume environments, magma-poor margins may reflect the inherited stage of the subcontinental mantle.

A common characteristic of many rifted margins is the occurrence of an outer high, in our models also referred to as bulge. Also outer highs can result from different processes, one of which is out of sequence polyphase rifting (Péron-Pinvidic and Manatschal, 2009), another can be related to magmatic additions in which magmatic thickening (MT) is larger than crustal thinning (CT). In situations where $MT > CT$, magmatic additions can build on existing crust, resulting in “sandwich” or “crocodile” type crustal architectures, representing “hybrid” crust. In such systems magmatic additions build either on inherited crust or mantle (Gillard et al., 2017, 2019). The location of the bulge relative to the margin allows the

characterization of the type of margins but also the timing of magma-production. When the bulge is built onto crust thicker than 10.5 km, magma generation is early with respect to extension (T_a) and the magmatic volume is normal to elevated. When the bulge occurs on continental crust < 10.5 km thick, the magma production can be explained by a standard depth uniform decompression model. If the bulge is built onto hyper-extended crust or exhumed mantle, magmatic production is delayed with respect to rifting. How the magmatic budget depends on the advance or delay of the start of magma production is difficult to determine, since in most examples it is difficult to determine the magmatic budget (Tugend et al. 2018).

5.3. Characterization and classification of the global rifted margins: limitations and perspectives

From this study it appears that by changing the budget and the relative timing of magma production with respect to lithosphere stretching and thinning, all types of OCT shapes observed at rifted margins can be generated. As a consequence, this allows a new approach to classify the world margins (see Figure 39). However, this classification approach presents some models that are not really observed. For instance, margins with delayed magma production and high magmatic budgets (T_d - B_h) are neither expected nor observed. In contrast, margins with advanced magma arrival and high budgets may be common, but how much topography that magma can build depends on the subsidence history, the composition/viscosity of the magma and if it occurs sub-areal or sub-aquatic. Future studies need to investigate if margins with mantle exhumation can show excess magmatic activity during breakup and what is the maximum crustal thickening that can be achieved by magmatic additions in syn-extensional settings.

In most examples advanced magma generation with respect to rifting is linked to high magmatic budgets and related to mantle plume related magmatic activity. Examples with low but advanced magmatic addition are less common and may be related to first alkaline magmas that are often observed to be produced in early rift systems (e.g. "moist" magma model by Braun et al.; Jagoutz et al., 2007; Grange et al., 2008). However, the volumes of such magmas are expected to be minor and difficult to observe in seismic sections.

Our simple model can account for the three key observations we can make on seismic sections from rifted margins, which are: 1) wedging, 2) stepping up vs. stepping down” onto oceanic crust, and 3) occurrence of magmatic bulges due to magmatic thickening. All these observables are indicators of the relative magmatic timing and budget and allow a classification of the global margins (Figure 38). However, this simple model does not enable the determination of the absolute timing between crustal thinning and magmatic breakup, which are considered in our simple model to be genetically related (in our model, the initiation of the magma production is directly linked to the thinning factor). In reality, at many rifted margins crustal thinning and magmatic breakup are not necessarily linked (e.g. Norwegian margin, where crustal thinning and breakup are separated by more than 60myr (Osmundsen and Ebbing, 2008)). However, since rifted margins represent a finite structure, the final architecture observed at a margin depends on the relative timing and stacking of tectonic and magmatic events, rather than on absolute ages.

6. Conclusion

From seismic interpretation, the first-order observations at magma-rich rifted margins are coinciding magma emplacement and crustal thinning, and a step down drawn by the top basement outline onto oceanic crust. At magma-poor margins, the first-order observations are mantle exhumation, separation of crustal thinning and first magma emplacement, and a step up drawn by the top basement outline onto oceanic crust). We demonstrate that at least two parameters need to be taken into account to describe the diversity of observed margin shapes; these are the relative timing of arrival of magmatic addition with respect to rifting and the magmatic budget. We show that advanced magma arrival and high magmatic budget are observed together to margins associated with a mantle plume environment, where hybrid crust can be observed and anomalous subsidence may occur. Magmatism can be present before lithosphere thinning and a clear overlap of rifting and magmatic activity is expected. The normal arrival of magmatism with respect to lithosphere extension with a normal budget, as used to define a standard margin model, show syn-extension magmatism with overlapping magmatism and deformation. Late magmatic arrival with low to normal budget are characteristic of margins where crustal thinning and magmatic activity are clearly separated by the mantle exhumation domain. We highlight that margins need to be defined by at least two parameters; not just the magmatic

budget but also the relative timing of the arrival of magmatism with respect to tectonic extension.

Chapter V: General

Discussion, conclusion & outlook

General Discussion, conclusion & outlook:

In my PhD thesis I aimed to provide some answers to a first order scientific question, which is how continents rift, break and oceans form in the presence of magma-rich systems. Trying to answer to this question asks to be able to observe, use quantitative methods and propose testable hypothesis that need, in turn, to be scrutinized by direct observations. I first had to find ways to address the problems, had to learn to use and apply methods and finally to develop an approach that was not defined at the beginning of my PhD. This took some time and in order to find answers, I had to define and develop a new approach that eventually enabled me to address three main scientific problems linked to key questions: how continents breakup in the presence of excess magmatic systems, how such systems can be described and restored, and what methods can be used to tell apart between magmatic and extensional processes.

In my PhD I was essentially interested in finding the first order characteristics of magma-rich rifted margins. The theory tells us that during the thinning of the lithosphere decompression melting should be generated (McKenzie, 1978; Katz et al., 2003). Despite the fact that processes and structures related to extension and magmatism have been well investigated, observations of natural analogues show that magmatic processes are yet difficult to predict, observe and introduce in conceptual and dynamic models. At present-day rifted margins, the magma production occurs at different stages of extension and with various budgets demonstrating that the current magma-poor/magma-rich classification is limited and cannot account for what happens during lithospheric extension and breakup. In most cases the presence of syn-tectonic extrusive magmatism inhibits a structural interpretation of the associated extensional system as imaging crustal structures occurring beneath thick magmatic material remains difficult. Therefore, defining the magmatic budget as well as the timing of magma production remains a major challenge. However, timing and budget of magma are fundamental to understand the evolution and processes related to

rifting and breakup of continents and the formation of new oceans. Moreover, in magma-rich settings, associated to plume and/or Large Igneous Provinces, kinematic restorations and tight fit reconstructions remain debated.

Based on these considerations, I defined three main questions that I tried to answer during my thesis:

1. How can rifted margins be characterized at a first order and what information can crustal shapes provide on the relative timing and budget of magmatic systems?
2. What methods and approaches can be used and/or developed to investigate magmatic additions at magma-rich rifted margins?
3. How to use kinematic restorations at magma-rich margins and how to restore the tightest fit reconstruction?

These questions form the foundation of my PhD and have been answered by using the Mozambique Channel as a natural laboratory. The access to seismic reflection and refraction data was fundamental but since their interpretation remains non-unique, I was forced to combine and test the results with other methods to assess the nature of the crust and use end-member scenarios to discuss the evolution of this complex geological system. In this last chapter of my PhD, the goal is to highlight the main results and to discuss them in the light of the main questions that guided the whole study as well as to show how the results of this PhD will impact the future investigation of rifted margins and the role of magma in breaking continents in general and the evolution of the Mozambique – Antarctica margin in particular.

1. How can rifted margins be characterized at a first order and what information can crustal shapes provide on the relative timing and budget of magmatic systems? (chapter IV)

Magmatism plays a major role in the way continental lithosphere breaks up (Geoffroy et al., 2015; Tugend et al., 2018). Many studies have analysed the magmatic processes, however when and how much magma forms are yet poorly defined. In this study we show that:

- The dual magma-poor magma-rich system does not enable to characterize all of the observed margin types
- Although margins are in detail complex, various crustal shapes of Atlantic type rifted margins can be reproduced by varying two parameters only (Figure 39): the magmatic timing (T) which can be anticipated (Ta), normal (Tn), or delayed (Td), and the magmatic budget (B) which can be low (Bl), normal (Bn) or high (Bh).
- Delayed magmatism results in margins where mantle exhumation is observed. Anticipated magmatism with magmatic production starting early in the development of the margins cannot be explained by decompression melting alone.
- Atlantic type margins tend to show end-member architectures.

The results obtained in my PhD study and summarize hereabove enable to propose a new, first-order characterization of rifted margins. The crustal shape, and more particularly the position and magnitude of the magmatic bulge, determines the timing and budget of the magmatic production. Thus, defining the first order crustal architecture and the existence of a magmatic bulge is a key to classify rifted margins and understand the relative timing of magmatic systems at rifted margins.

A main question is what processes can explain delay or anticipated magma as well as the budget of magma. Chenin et al. 2019 suggested that low magmatic budgets and a delay can be both related to an inherited depleted mantle. White and McKenzie (1989) suggested that low extension rates may be important. Another question is also if all types of margins

shown in Figure 39 exist in nature. For instance, do Ta-BI margins form, i.e. can anticipated magma have low magmatic budgets, or would it not be expected that anticipated magma, in most cases linked to plume settings, should result in high magmatic budgets. Another question, is if high magmatic budgets should not results in breakup, as suggested by (e.g. in Peron-Pinvidic and Osmundsen, 2016), in which case Td-Bh should not exist, unless they are polyphased.

In rift systems with high magmatic budgets (Bh), several processes can be responsible and can explain high melt production such as : hot/wet spot (Katz et al., 2003), thermal state of the mantle, the origin of a plume (Franke, 2013; Geoffroy et al., 2015), and the occurrence of an enriched mantle composition. Moreover, Bh-type margins are likely to show anticipated timing because of the mantle conditions. Magma-rich break-up can however be possible in a late stage of the margin evolution in cases where a plume is hitting a failed hyperextended rift system, as is the case for the N-Atlantic (Peron-Pinvidic and Osmundsen, 2016; Tugend et al., 2018).

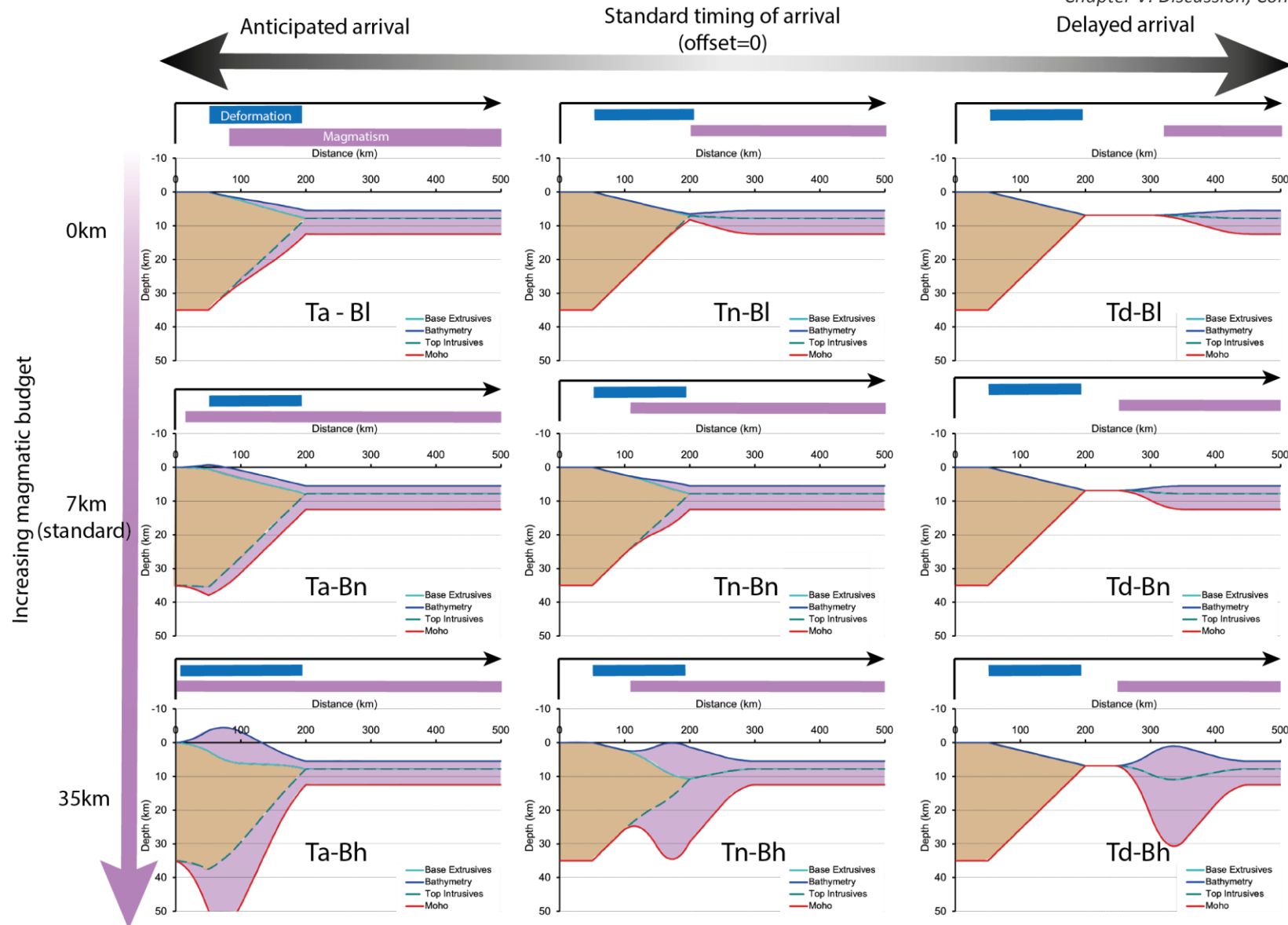


Figure 39: Represented, thermally equilibrated margin shapes based on different budgets and timing in magma production. Top horizontal axis represents the relative timing of arrival of magmatism compared to standard. Vertical axis represents the magmatic budget and initial thickness of decompression melting. The brown colour represents continental crust and purple represents magmatic addition. The diagrams on top of each margin show the relative position of magmatic processes (purple) compared to the thinning of the crust (blue).

One of the main conclusions of this study is that the magmatic budget alone is not sufficient to characterize rifted margins. The timing is also important and has to be considered when interpreting margins at first order. Key questions that remain and need to be investigated in future research are:

- How can processes and parameters controlling the magmatic budget, such as thermal state of the mantle, existing of “wet-spots” and compositional inheritances, and extension rates be observed, defined, understood and integrated into models of passive rifted margins where the access to samples and kinematic data is notoriously missing.
- How do plumes control the evolution of rift systems and what role do they play in the breakup of continental lithosphere? Many studies have analysed the relationship between the plume and the break-up of the lithosphere (White and McKenzie, 1989; Franke, 2013; Geoffroy et al., 2015). However, the propagation of the rift relative to the plume location is debated as discussed by Franke, (2013) who observed that the propagation of the rift is different from what is expected in classical rift models.
- How to characterise and define the nature and evolution of hybrid crust and what methods can we use to investigate hybrid crust? In Figure 39, we show that magmatic additions create a bulge onto continental crust (e.g. model Ta, Bh). Such a crust is defined as “hybrid crust” and is therefore difficult to characterize. In my PhD, however an attempt has been made to study such hybrid crusts using the example of the Mozambique margin.

2. What methods and approaches can be used and/or developed to investigate magmatic additions at magma-rich rifted margins? (Chapter III)

In my study I defined hybrid crust as a continental crustal domain that has been thickened by syn-rift magmatic additions. However, as demonstrated by Tugend et al. (2018), it is difficult to defined and quantify the volume of magmatic additions in thinned

continental crust. Hybrid crust, as defined here, is characterized by: 1) inherited, thinned continental crust sandwiched in between extrusive syn-tectonic and dense intrusive and underplated magmatic additions, 2) “plume” thermal support or dynamic uplift during its formation, and 3) a distinct isostatic evolution, i.e. it is too shallow first and then too deep at a later stage for the observed crustal thickness.

In my study, I used gravity inversion, joint inversion, and subsidence analysis to investigate the nature of crust flooring the Mozambique Coastal Plains (MCP) and Northern Natal Valley (NNV). Details of the methods are presented in Chappell and Kusznir, (2008), Cowie et al., (2017). The MCP and the NNV correspond to hybrid crusts presenting high density, possibly picritic material (Bristow, 1980). The main aim was to define the proportion of magmatic additions and thinned inherited continental crust flooring these two domains, which has major implications on the thermal evolution and for the restoration. The results show that:

- Gravity inversion enables to propose crustal thickness maps.
- Joint inversion of Moho depth using refraction data and the gravity data enables to calculate the distribution of crustal densities and also to define the thinning factor and to provide the remaining continental crustal thickness, which shown that the crust is composed by relatively high density material, which question the crustal thickness evaluation by results of Moulin et al., (2019) of up to 40km. In this study, I propose a high proportion of up to 50% of magmatic addition in the crust flooring the MCP and NNV.
- Subsidence analysis, the water loaded subsidence compared with the observed subsidence (defined from well data) demonstrates the impact of the thermal support. Therefore, during the formation of the hybrid crust, the system is thermally supported by the plume (at least 500m of dynamic topography according to the analysis). The possible arguments to support this are the erosional surfaces that are visible on seismic lines on the MCP.

Quantification methods have been used successfully on magma-poor rifted margins (Cowie et al., 2017) and only very recently, these methods have been used on magma-rich systems (e.g. Harkin et al., 2019). The results of this study confirm that they can be used in

magma-rich settings, although improvements will be necessary to really get well constrained, and non-unique results. In particular, the imaging techniques need to be improved, new and better geological observations are required to fully understand the development of hybrid crust. At present, all results lack calibration and no good analogue exists for present-day hybrid crust formed at a volcanic rifted margin.

Finally, extending these methods to other debated systems in relation with plume and/or heavy magmatic systems might help in their interpretation. Examples are the Afar margins (d'Acremont et al., 2005; Stab et al., 2016; Nonn et al., 2019), southern Brazilian margins (Evain et al., 2015; Harkin et al., 2020), Jan Mayen margins (Blischke et al., 2017). Improving the interpretation of magma-rich rift systems is furthermore important in order to propose kinematic restorations of such systems.

3. How to use kinematic restorations at magma-rich margins and how to restore the tightest fit reconstruction? (Chapter II)

The restoration of the Mozambique Channel leading to the tight fit between Antarctica and Africa is still debated (Thompson et al., 2019). In my PhD, I revisited the problem of restoring magma-rich systems by investigating the Mozambique-Antarctica rifted margins. In order to do it, I developed a new method that consists in end-member scenario testing with different magmatic budgets and/or kinematic frameworks (Figure 40). The most important result of this study is that in contrast previous models that proposed that the most likely Ocean-Continent Transition are either igneous crust in the MCP and NNV, or of entirely continental origin (Figure 40), the best fit scenario can be obtained with a hybrid crust with 50% of magmatic and 50% of initial thinned continental crust

These results are in line with seismic interpretations that allow to draw limits of identified crusts (full thickness continental crust vs Penrose oceanic crust) and to propose a transitional area that can be either continental, magmatic or hybrid. The scenario with hybrid crust can also account for the main pin points. The detailed composition, nature, and history of this crust remains debated, however in Chapter 3, I was able to demonstrate that this solution is in line with geophysical modelling.

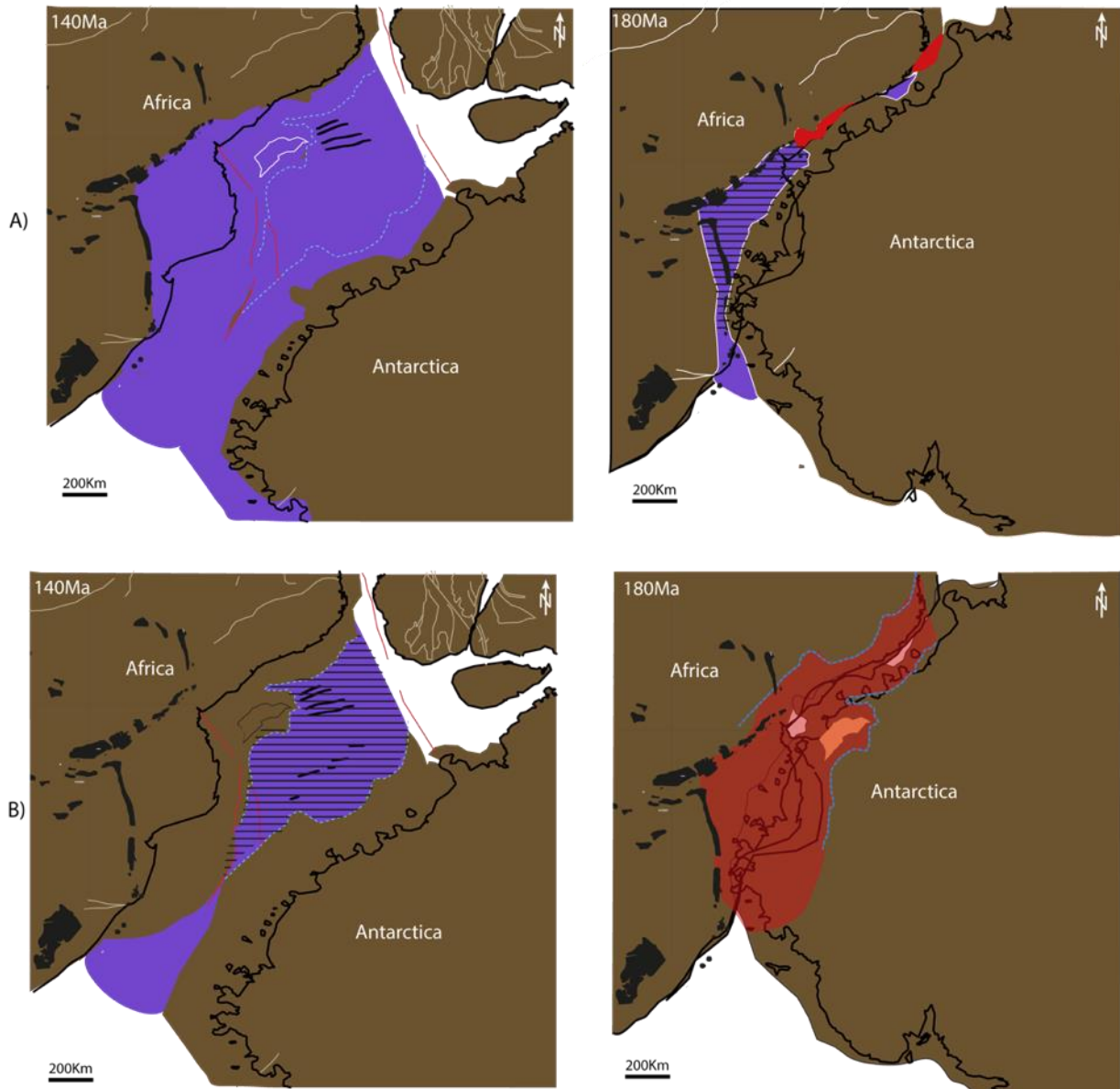


Figure 40: Magmatic end member scenario: The Mozambique Coastal plains are underlain by magmatic crust and the Beira High is a magmatic Plateau. When restored, the region shows regions of gap that still need to be restored as well as some small overlap b) Continental end-member: The Mozambique Coastal Plains and the northern Natal Valley are composed of a 30Km thick continental crust and the Beira High is a 25Km-thick continental ribbon. When restored, the system shows clear overlap along the whole margins. Overlap are shown in red and gaps are shown by striped area.

The method proposed in this study enables a restoration, which is not definitive but a most likely scenario fitting the main pin points (Figure 41). Such approach can be extended to other systems where magmatism hinders a good interpretation and restoration of the crustal structures. Other similar study cases are the Sao Paulo margins (Evain et al., 2015), the SE Indian margin (Tugend et al., 2018; Harkin et al., 2019), Iceland (Foulger et al., 2019)

where the crustal nature and/or the transition to oceanic crust are still poorly constrained and, finally, where different scenarios can be proposed.

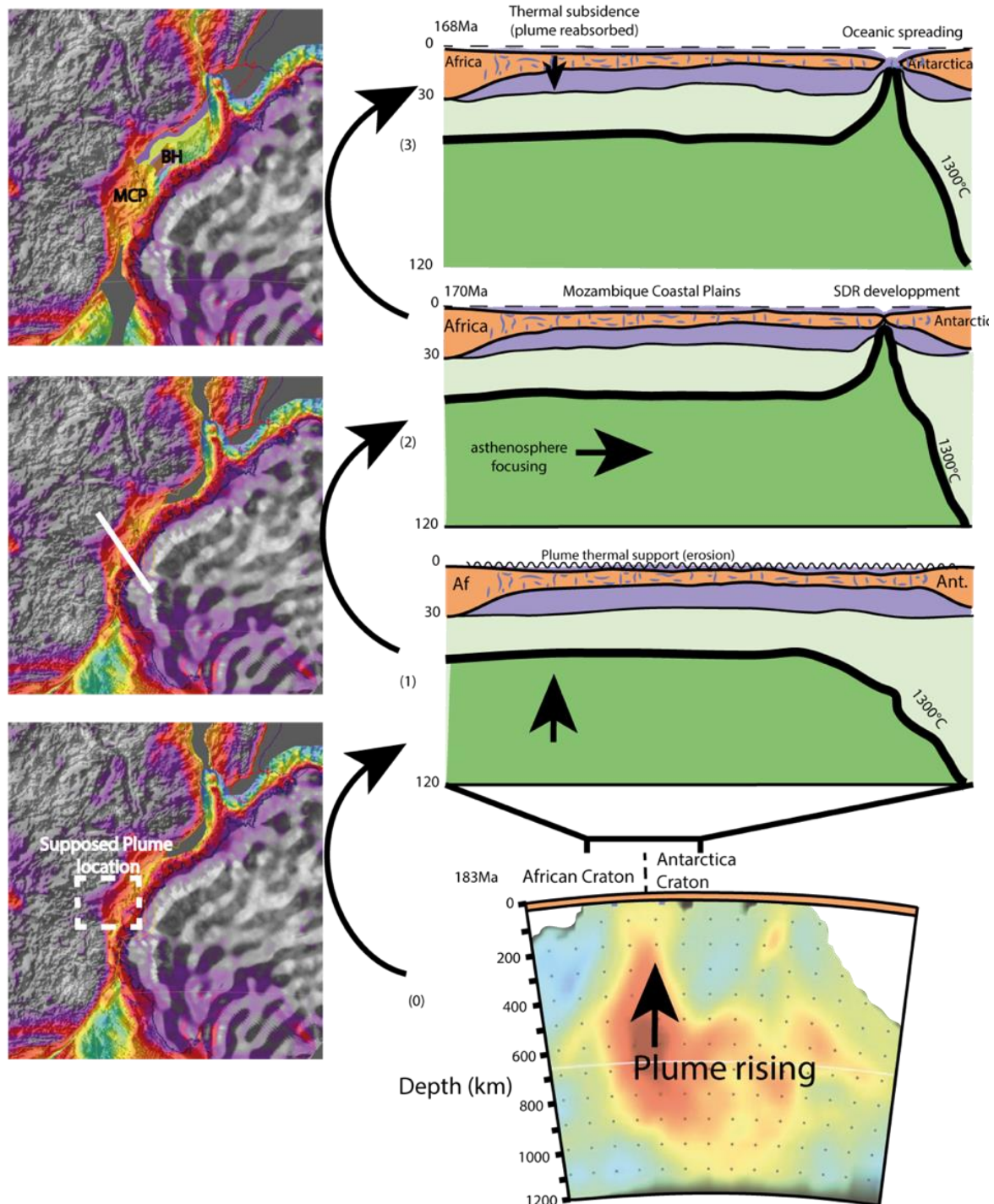


Figure 41: Schematic evolution of the Mozambique-Antarctica magma-rich extensive system. (0) Tomography picture is shown here for a scale indication of a mantle plume after Koptev et al., 2015. (1) Plume is rising, producing melt as the lithosphere is thinned. This magmatic addition maintains crust to a certain thickness balancing the crustal thinning. (2) The magmatic pulse is over, SDRs may develop. (3) Lithospheric breakup occurs and oceanic spreading begins. Maps indicates the associated plate reconstruction.

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Annexes

In order to answer the key questions asked in the Ph.D., several datasets have been interpreted. In the following section, I present firstly a few seismic examples of the Mozambique (which are degraded and not located for confidentiality issues), some lines from Antarctica margins which allows me to map domains. Then, I present some of the gravity inversion results with the input dataset, the joint inversion results, and subsidence analysis, Gplates screenshots.

1. Seismic Data

In this section, I present some examples of the seismic lines that has been interpreted during the 8 months period in Total. This allows me to map domain, basement structures and fault when possible (i.e., not masked by magmatism) and analyse the segmentation of the margin. In this section, I firstly show lines offshore North-Eastern Mozambique, then some lines crossing the Beira High, lines from offshore eastern Mozambique Coastal plains and then some lines from offshore Antarctica (see Figure 42).

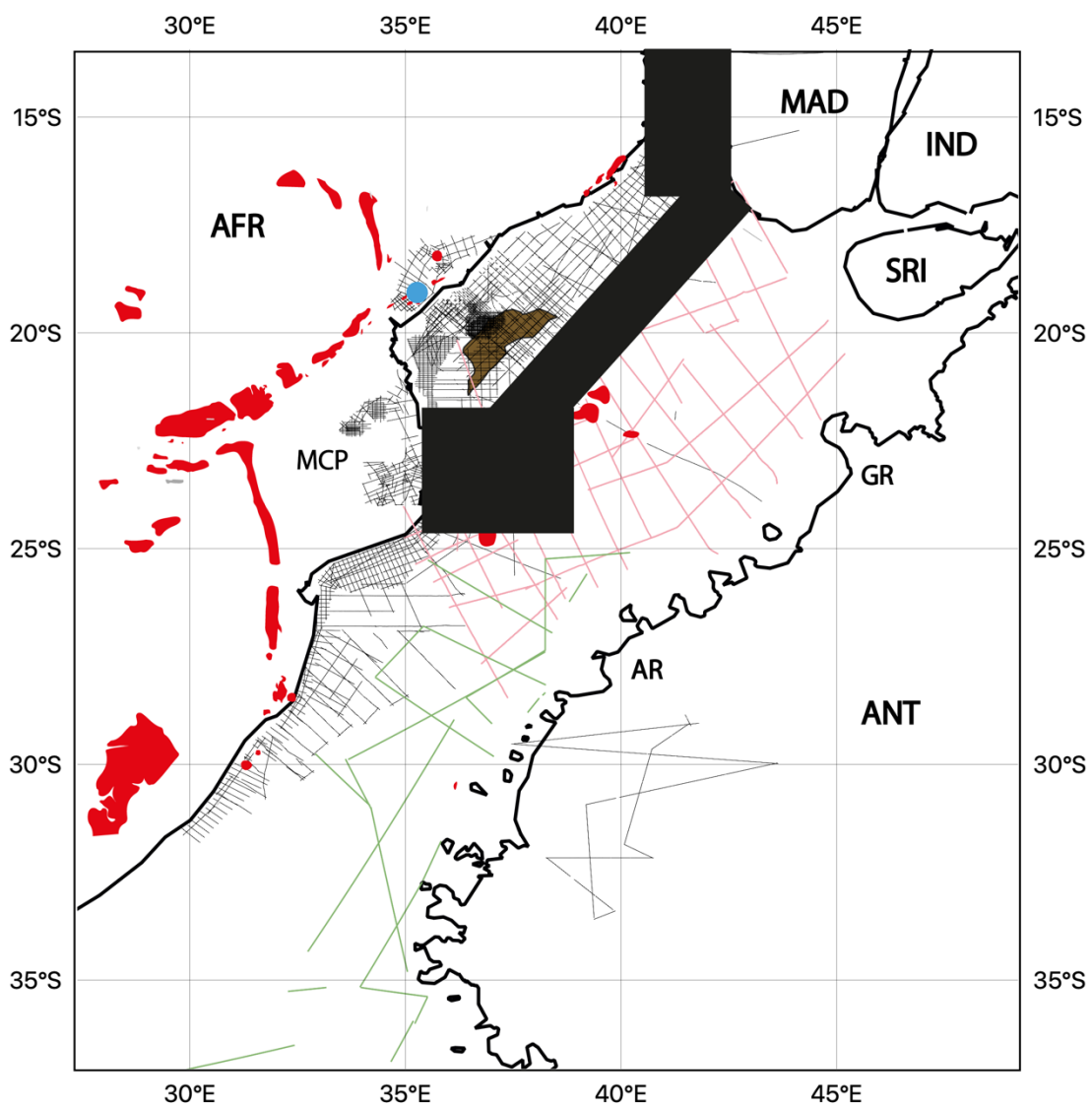
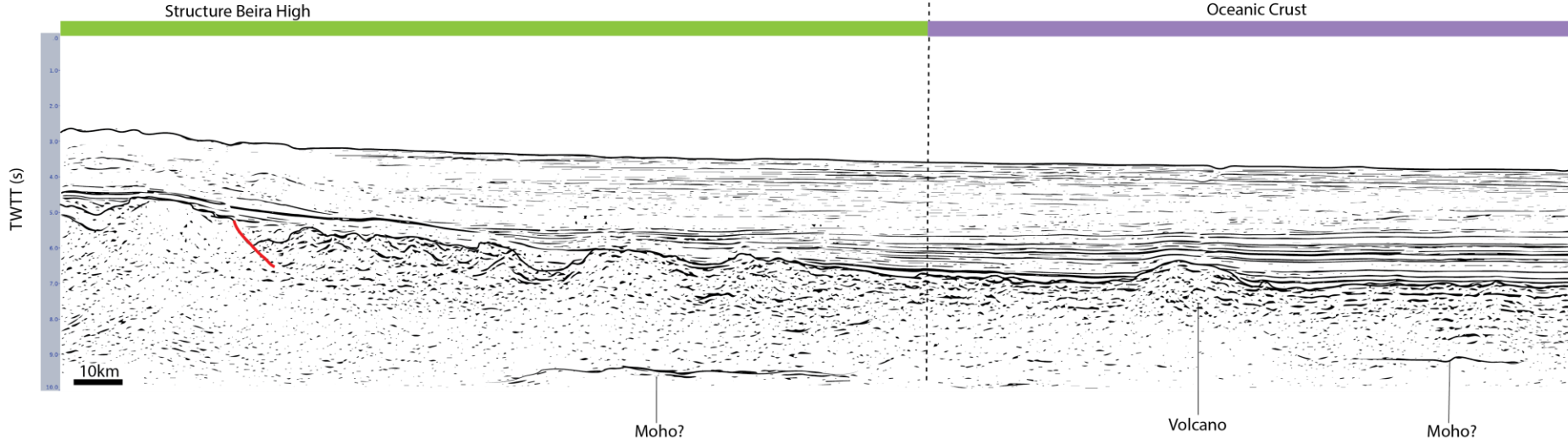
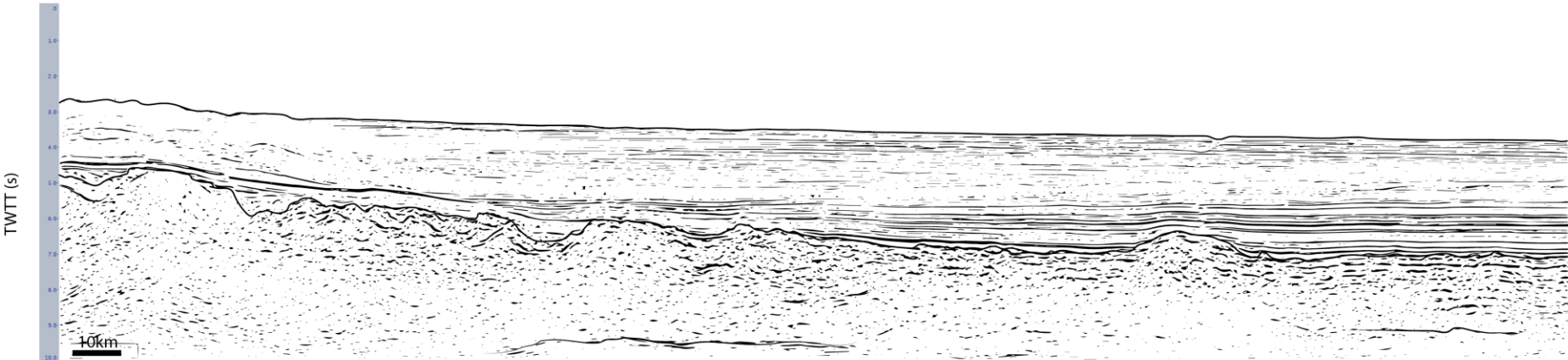
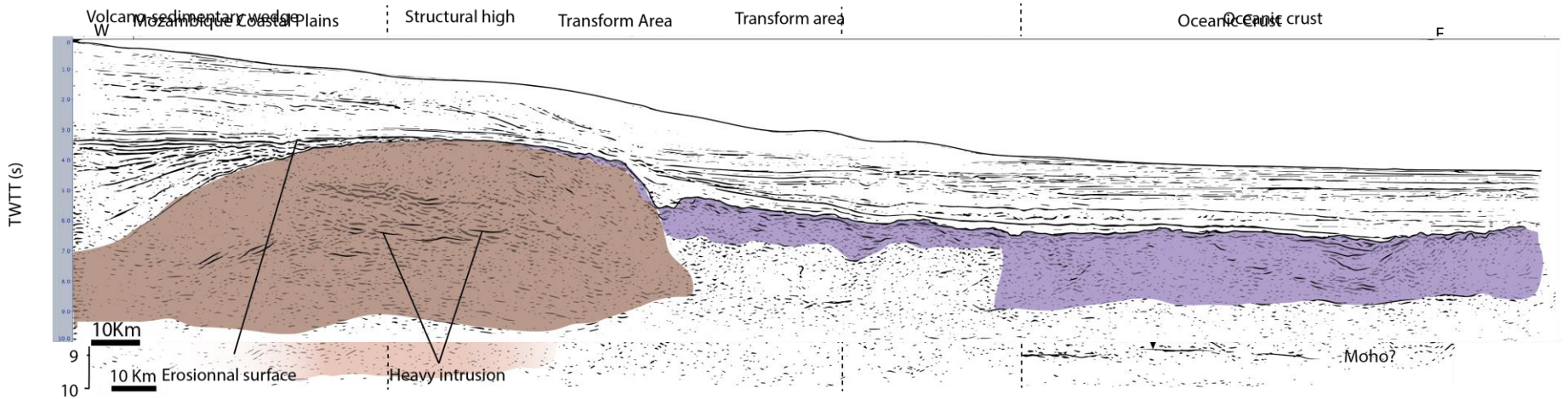
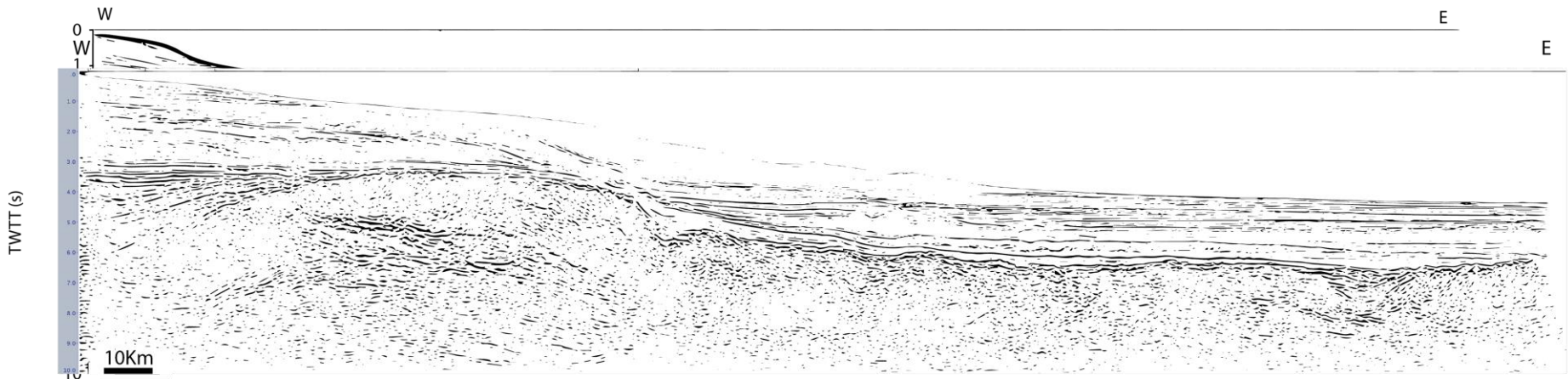


Figure 42: Restored map at 140Ma (poles of Davis et al.,2016) giving an overview of the seismic reflection datasets. Black lines represent the East African Dataset. Green and red lines represent dataset of offshore Antarctica.

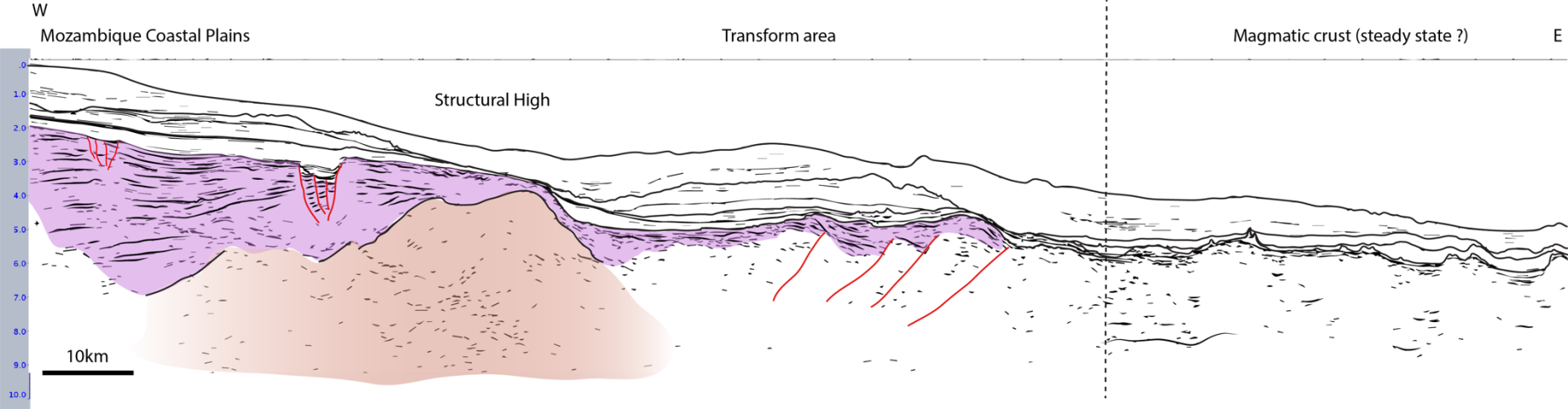
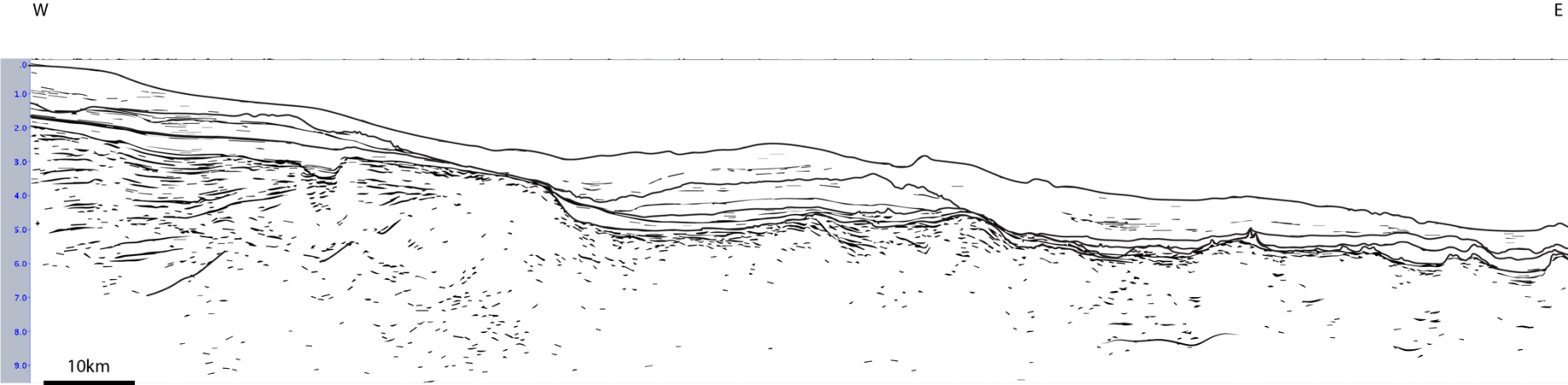
Segy file from Antarctica seismic survey can be found at:

<https://sdl.s.ogs.trieste.it/cache/index.jsp>





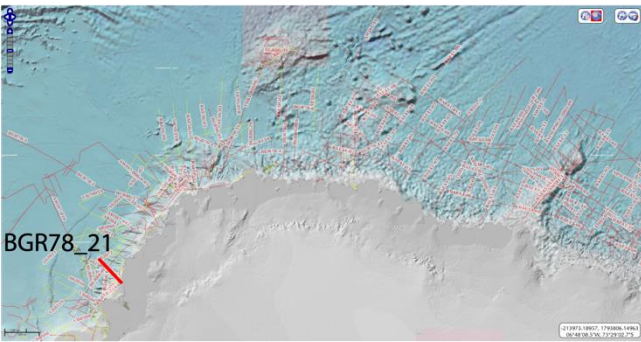
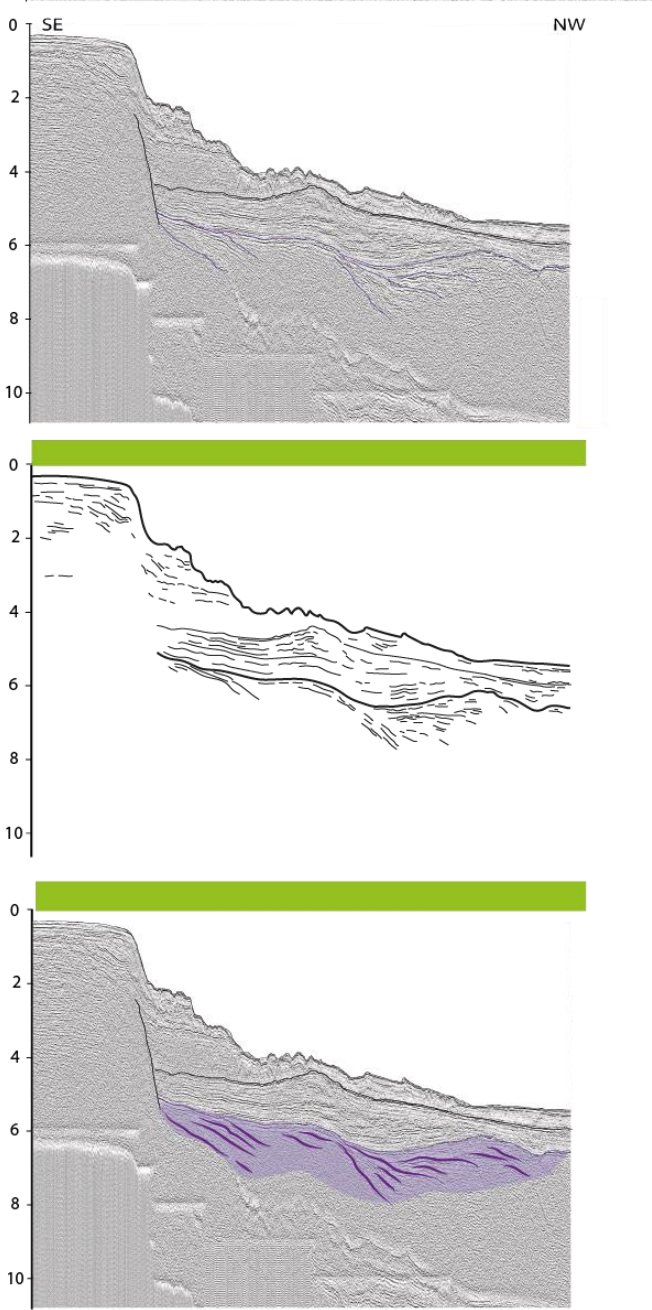
- Continental crust
- Magmatism
- Cretaceous sediments
- Tertiary sediments

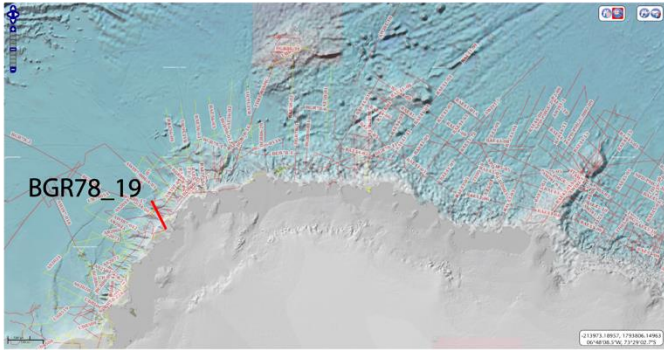
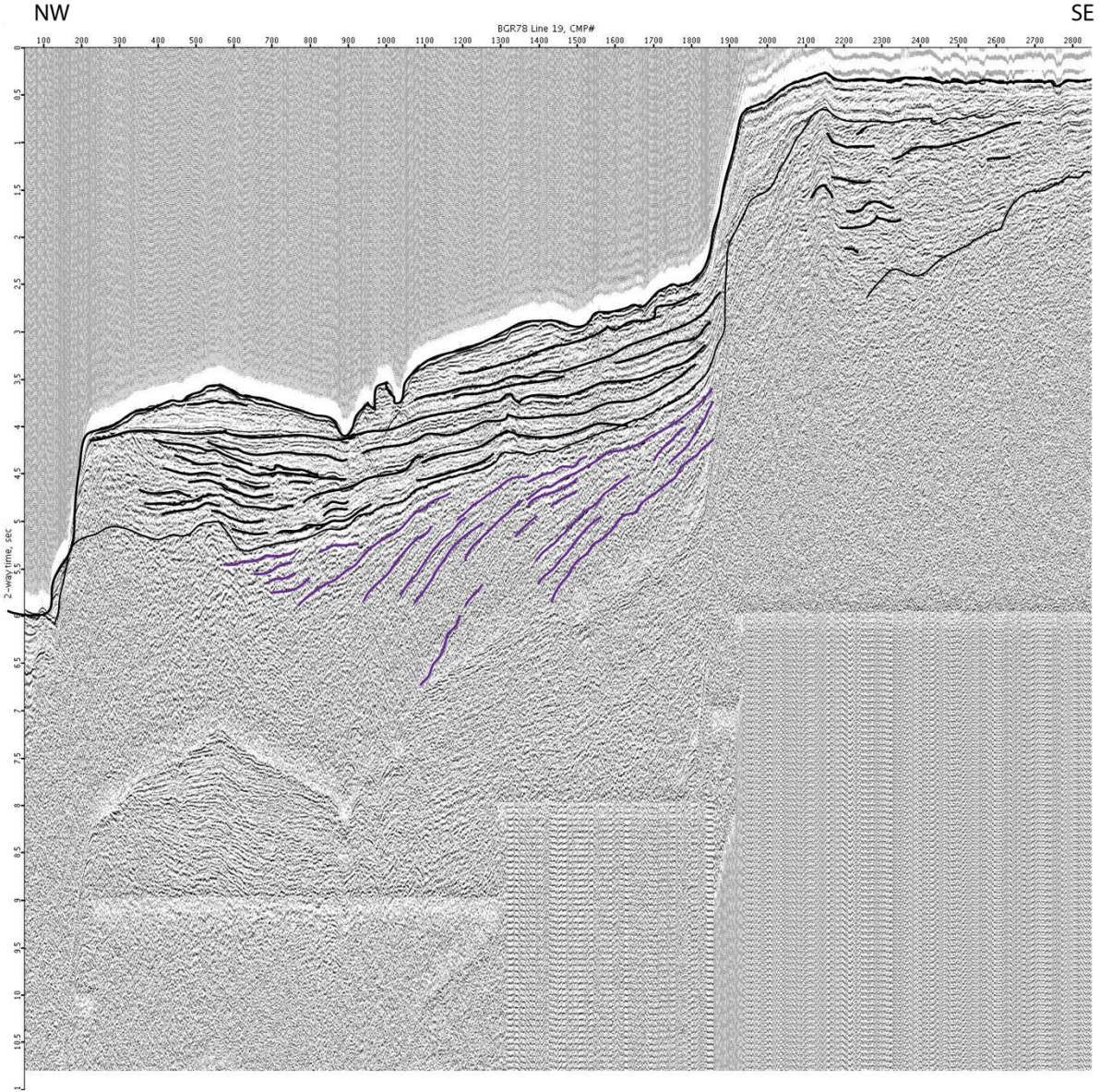


Continental crust
Magmatism

a

Antarctica dataset





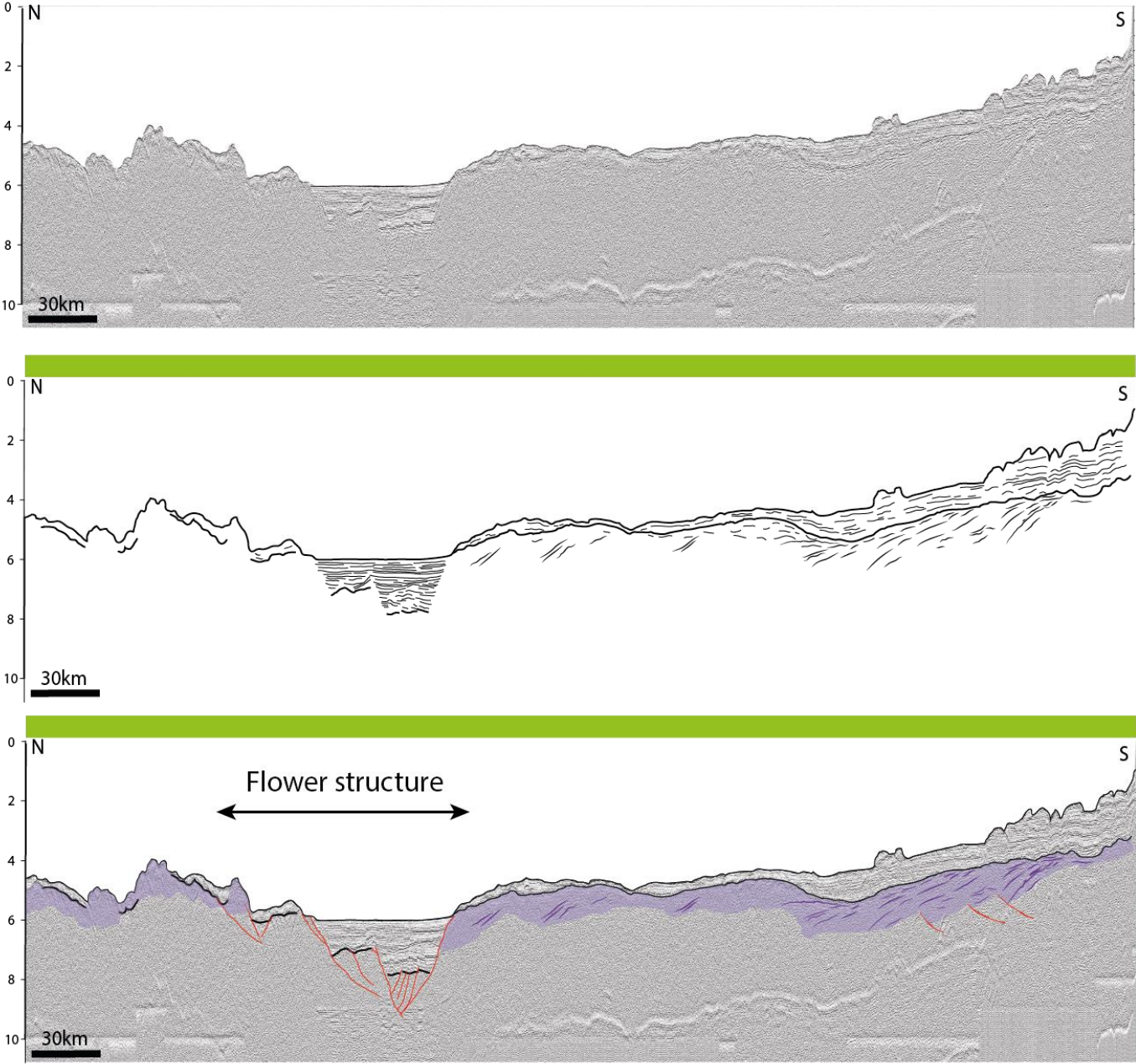
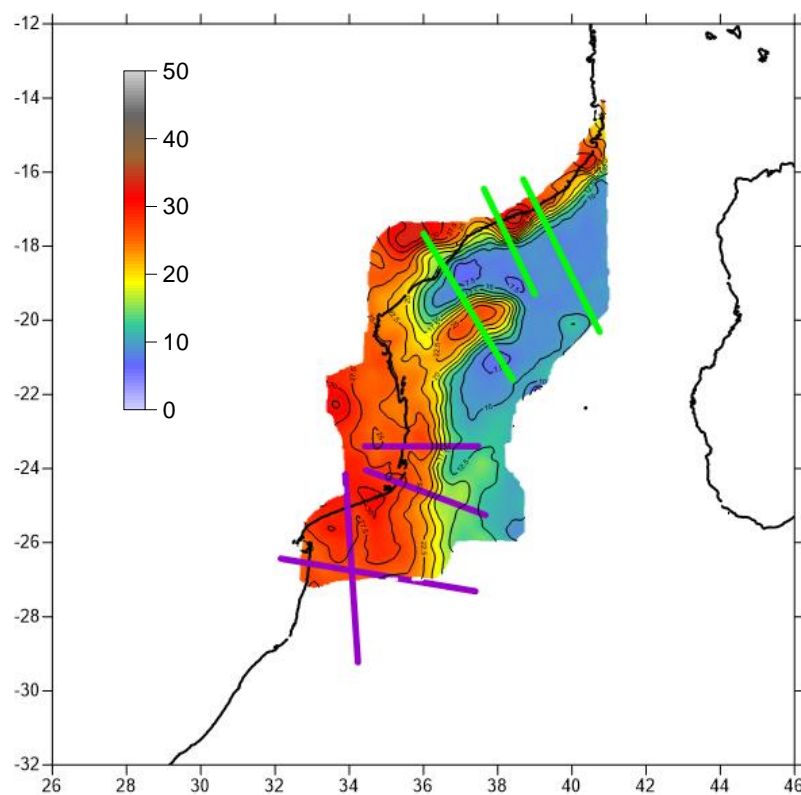


Figure 43: Examples of seismic reflection data interpreted during this study.

2. Gravity Inversion

In this section, I present the full set of data resulting from the gravity inversion that has not been presented in the manuscript. The gravity inversion method is described in (Chappell and Kuszniir, 2008). A detailed description of the gravity inversion method can be found in Greenhalgh and Kuszniir, (2007), Chappell and Kuszniir, (2008), Alvey et al., (2008), Kuszniir et al. , (2018). The gravity inversion method is carried out in the 3D spectral domain and incorporates a lithosphere thermal gravity correction (which in this case of an old thermally re-equilibrated continental margin lithosphere is not large). For the assumptions made (see Chappell & Kuszniir 2008), the gravity inversion method produces a unique solution for 3D Moho depth by invoking Smith's theorem, (1961). The input data required for the gravity inversion is 3D bathymetry, free-air gravity anomaly and sediment thickness. Here I present the results using the industrial top basement data.

Crustal Thickness From Gravity Inversion (km)



Gravity inversion using TOTAL sediment thickness grid

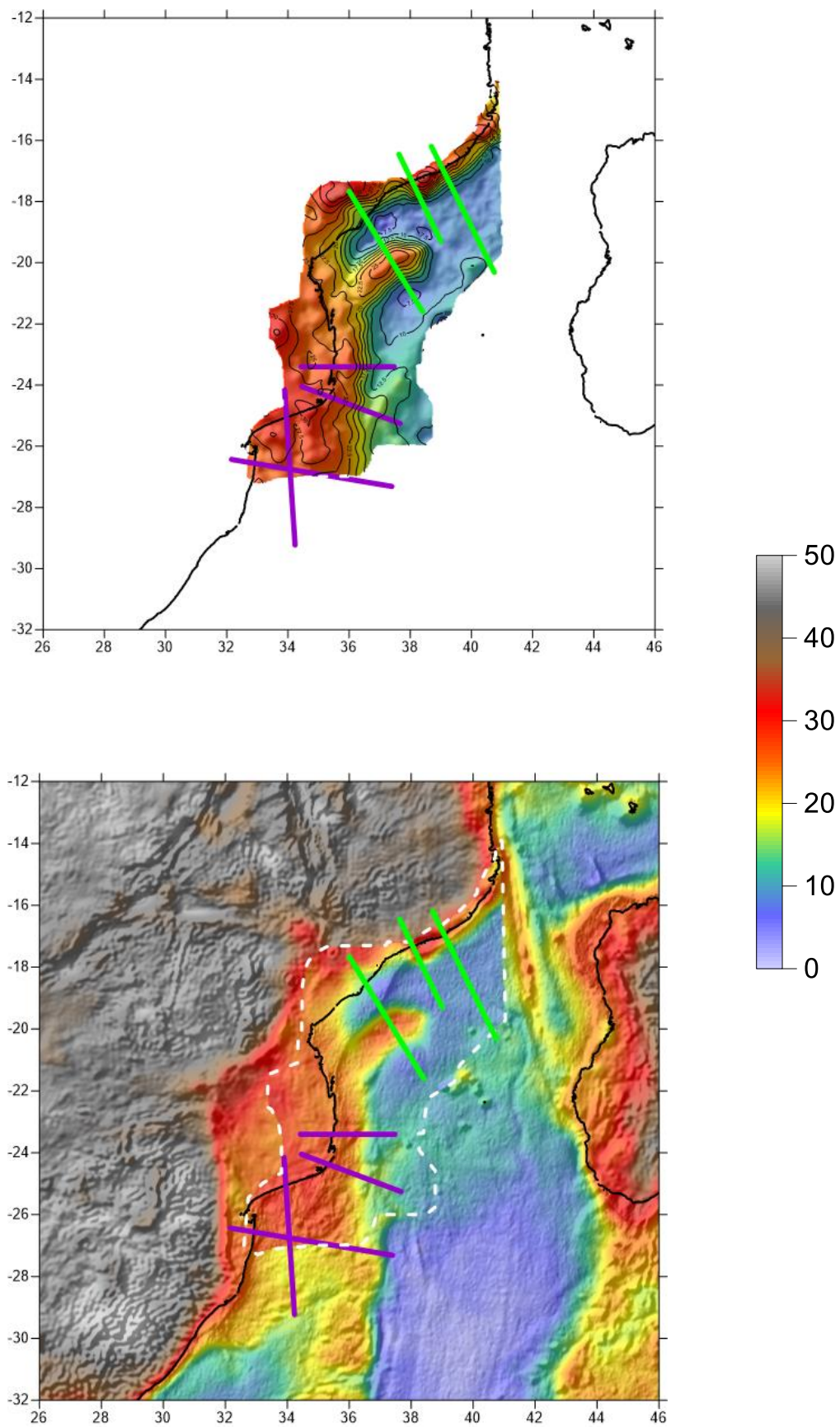


Figure 44: Compilation of 3 crustal thickness maps from gravity inversion using Total top basement interface. Total data coverage is delimited by the with dashed line (in km).

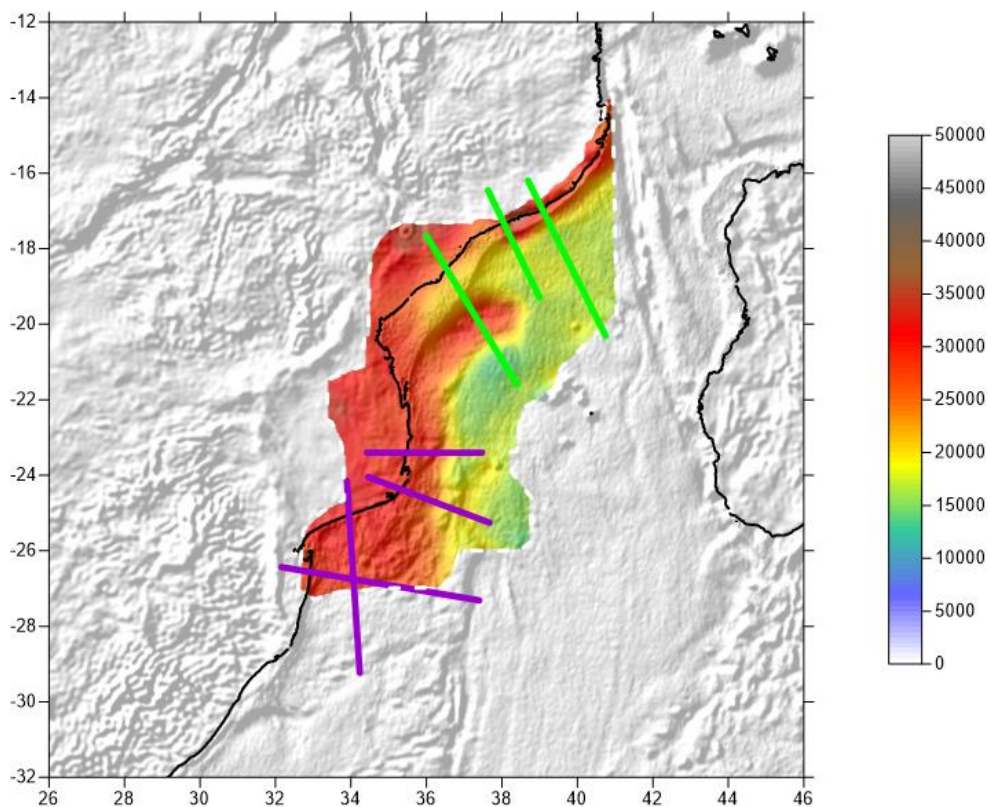


Figure 45: Moho depth map (in m)

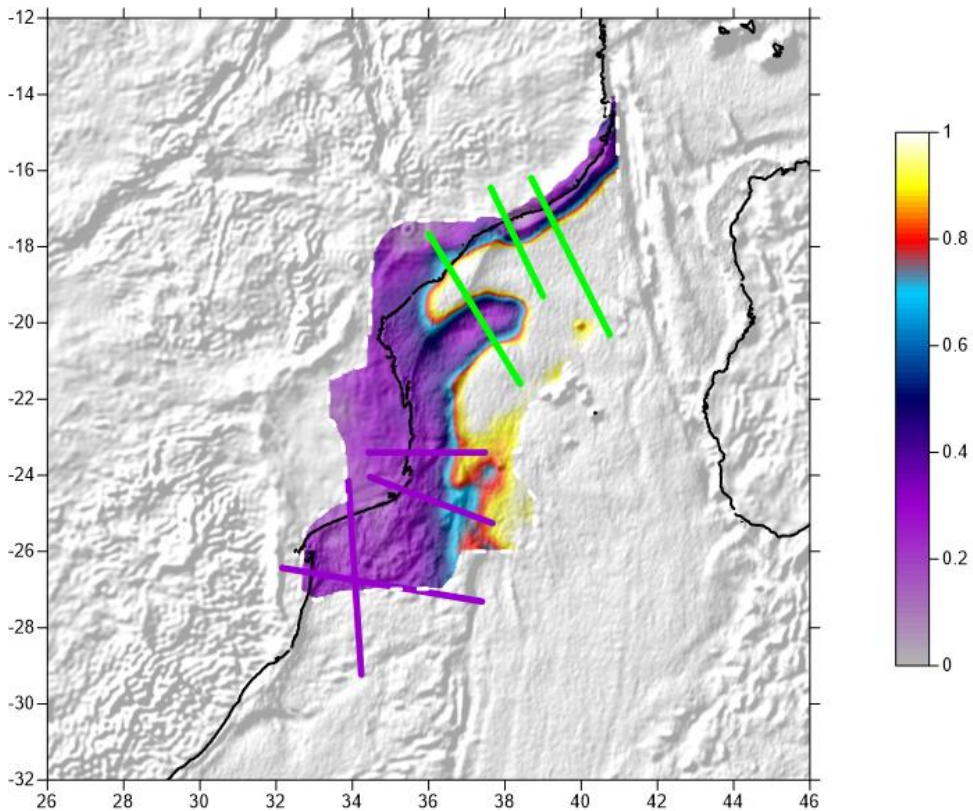


Figure 46: Thinning factor map ($1-1/\beta$).

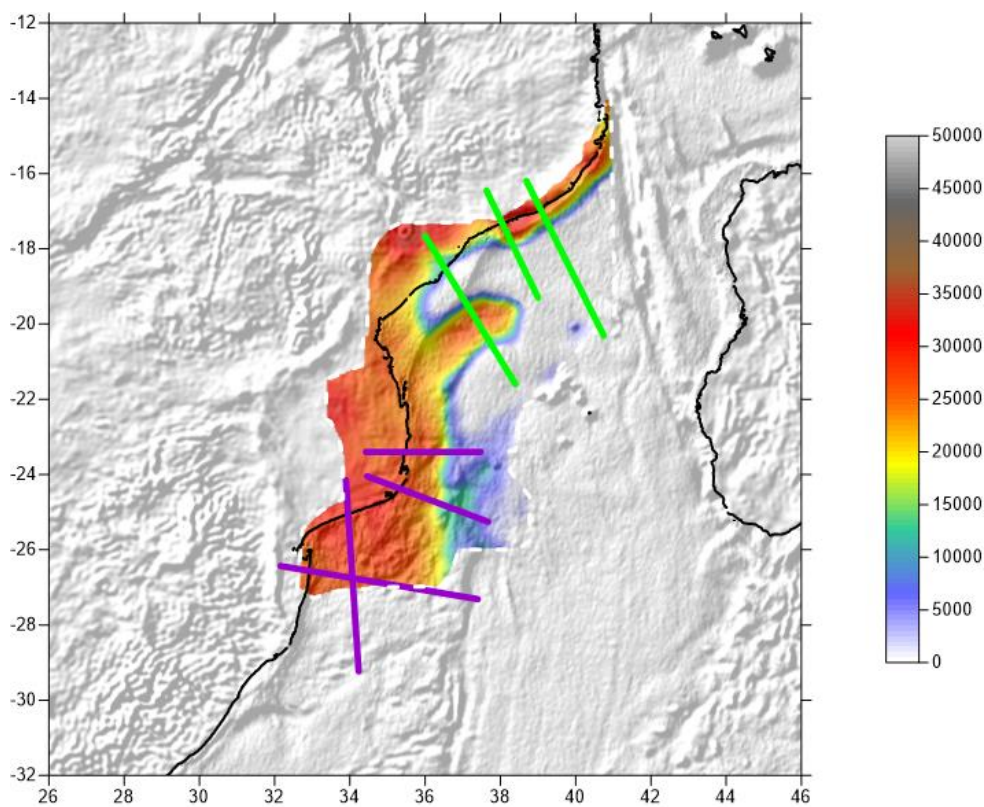


Figure 47: Residual Continental crustal thickness (in m).

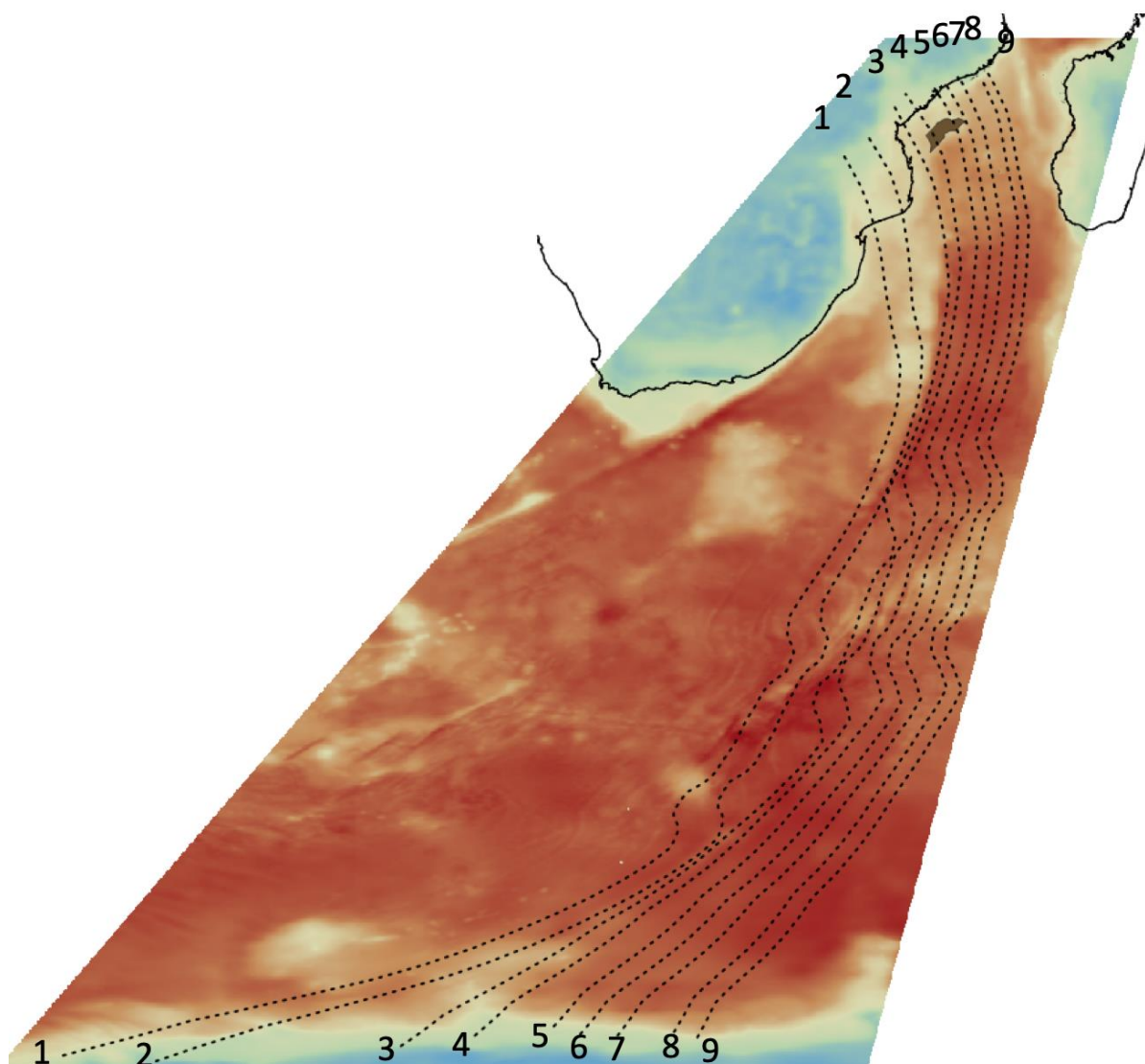
Crustal thickness integration along profiles

During the study, I try a method to highlight the excess of crustal material from one margin segment to another. Thereafter are presented the summary of this method and the details of each trajectory.

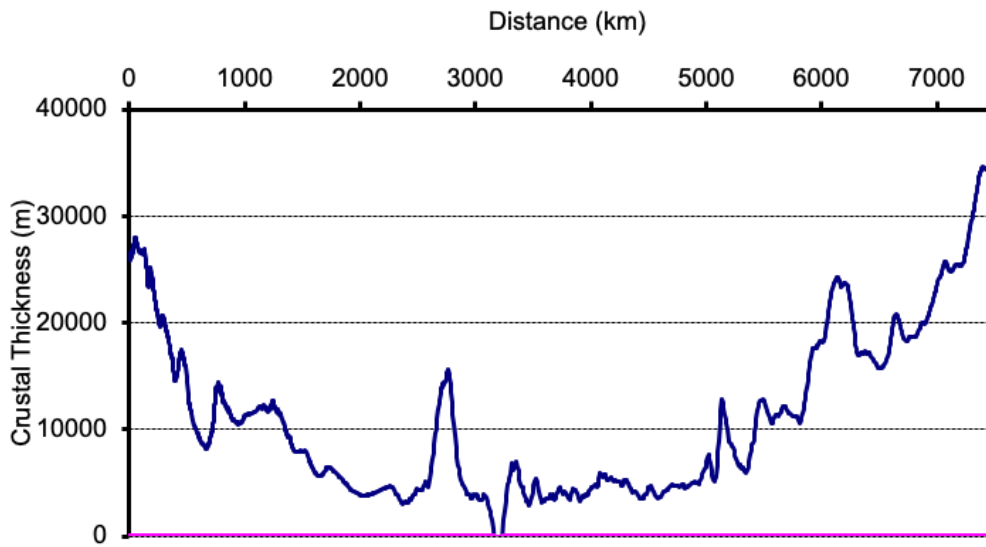
	Profile 1	Profile 2	Profile 3	Profile 4	Profile 5	Profile 6	Profile 7	Profile 8	Profile 9
Length of the profile:	7490.98376	7364.23092	6731.69579	6593.78364	6402.7405	6446.1595	6428.9539	6304.39335	6411.17827
Integrated Total Crustal Thickness:	83055.3625	83323.6073	57067.1728	47481.1307	43530.1985	44978.0209	46390.9805	46041.3697	49980.6755
Integrated total extension:	5748.08572	5697.70189	5772.16524	5893.99141	5877.43024	5822.02183	5764.48562	5627.28703	5631.07472
Mean value of integrated crustal thickness:	Limpopo: 83189.4849			Beira: 45329.7834			Angoche: 47471.0086		
Normalised Crustal thickness to profile length:	11.0873772	11.314638	8.47738438	7.20089304	6.79868229	6.97749115	7.21594543	7.30306108	7.79586425
Mean value of normalised integrated crustal thickness:		11.2010076			6.99235549			7.43829025	

Close to 2 times the amount of Crustal material for the Limpopo's Profiles

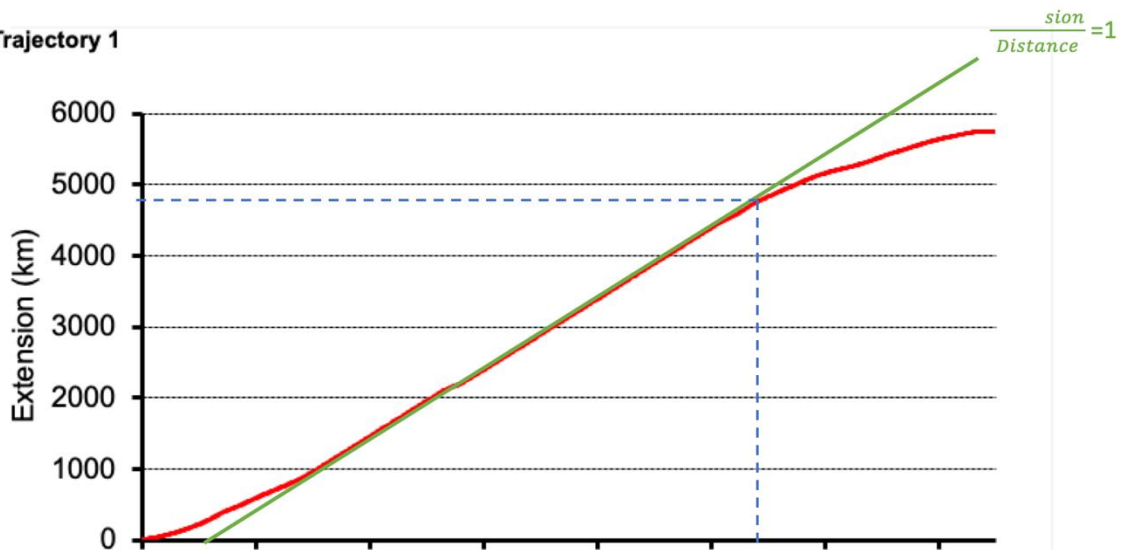
To check if the length of the profile has a influence on the result, I've normalised the integrated crustal thickness to the length of the profile:
There is still more crustal material on the Limpopo side



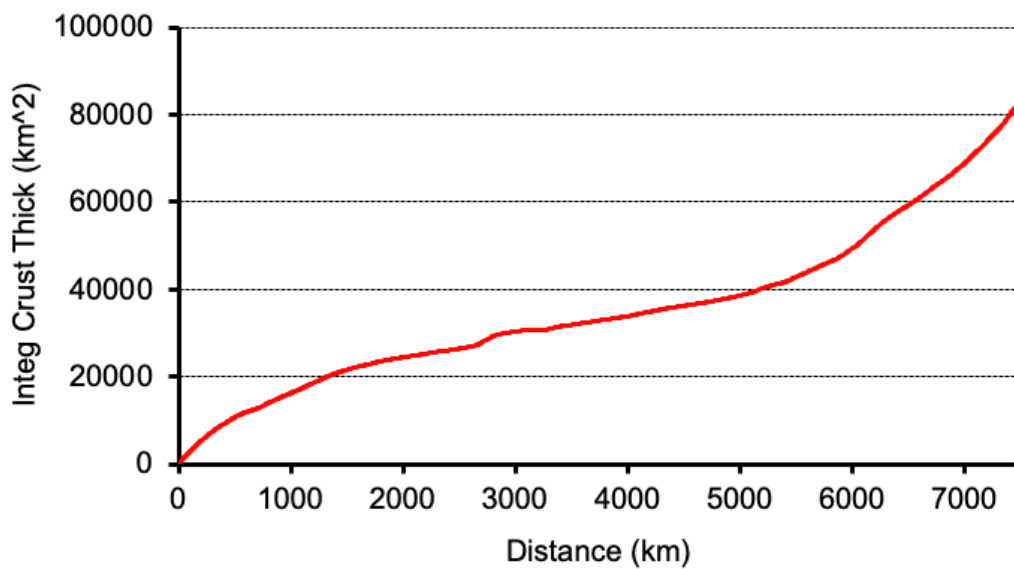
Trajectory A

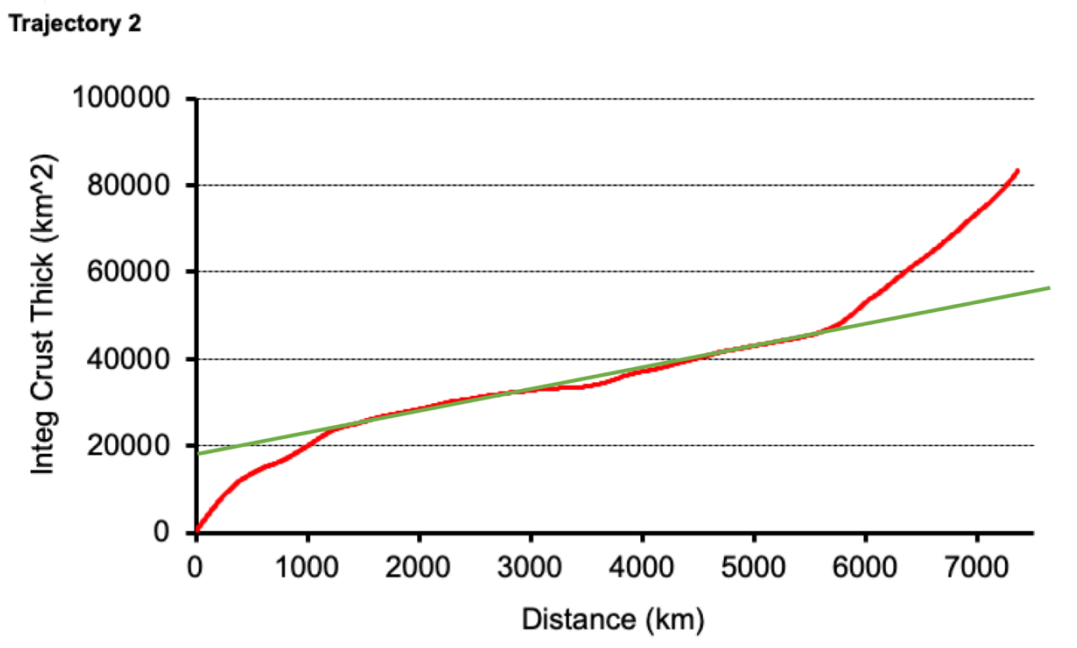
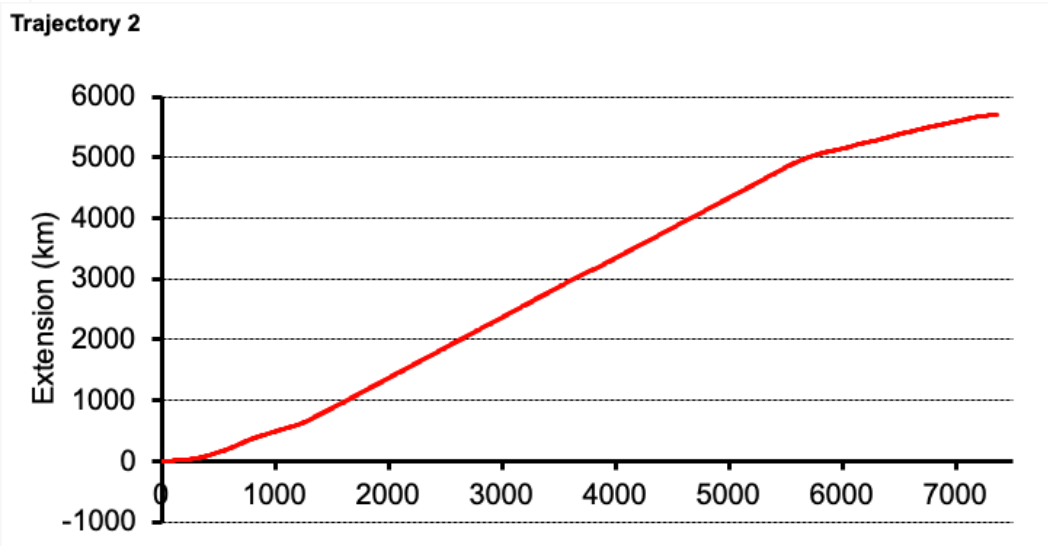
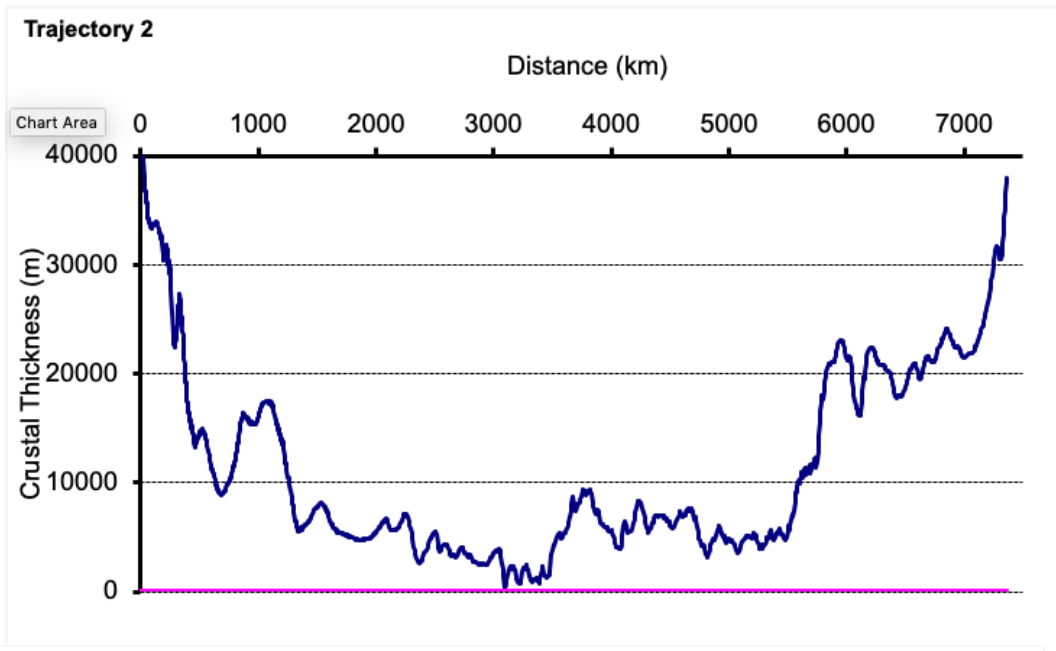


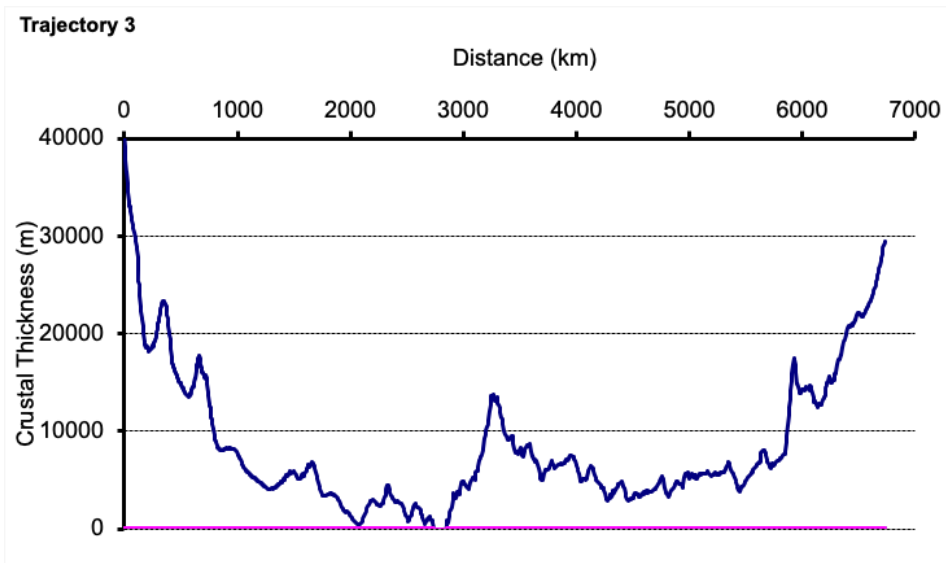
Trajectory 1



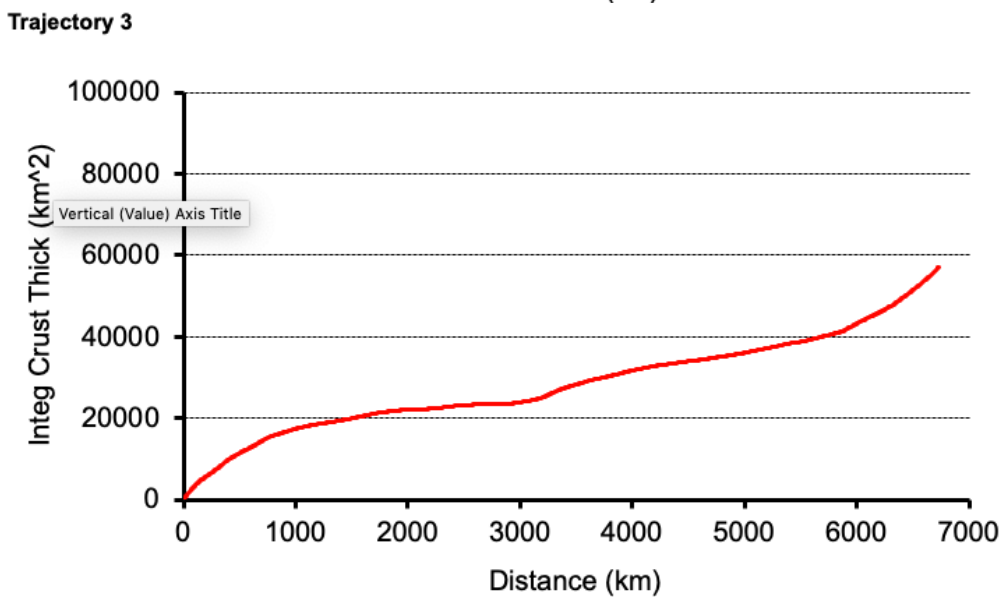
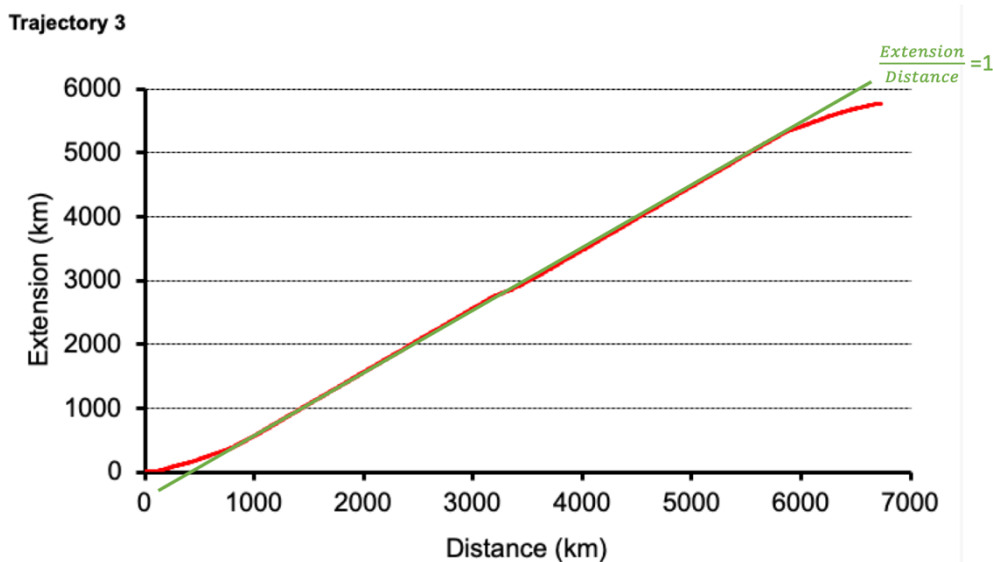
Trajectory 1

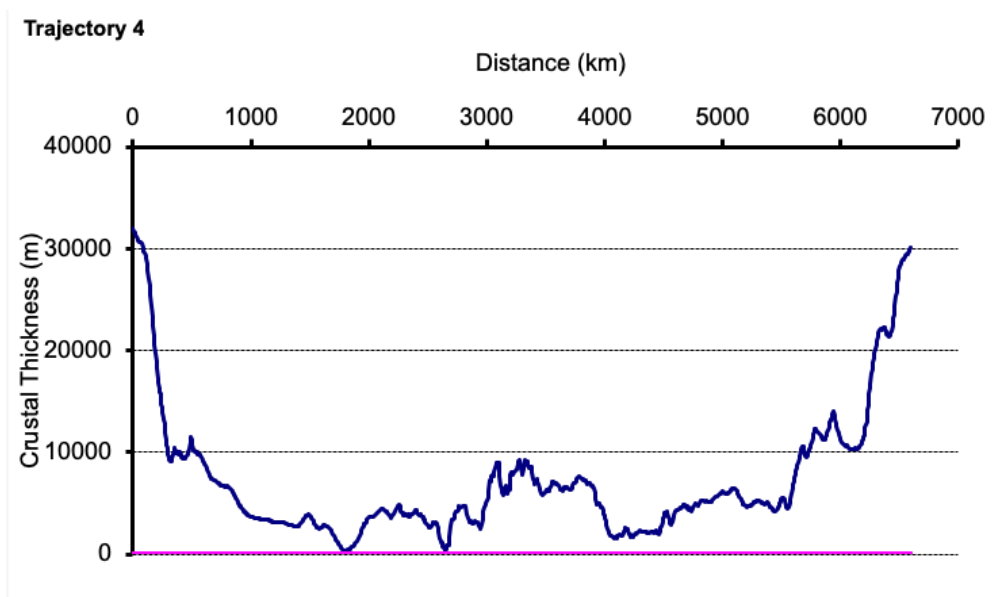




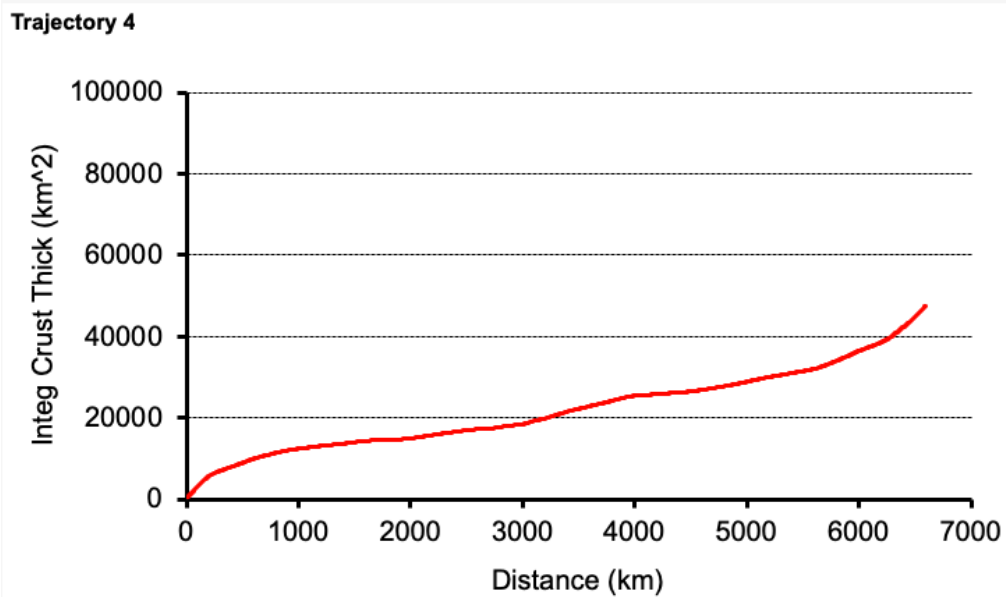
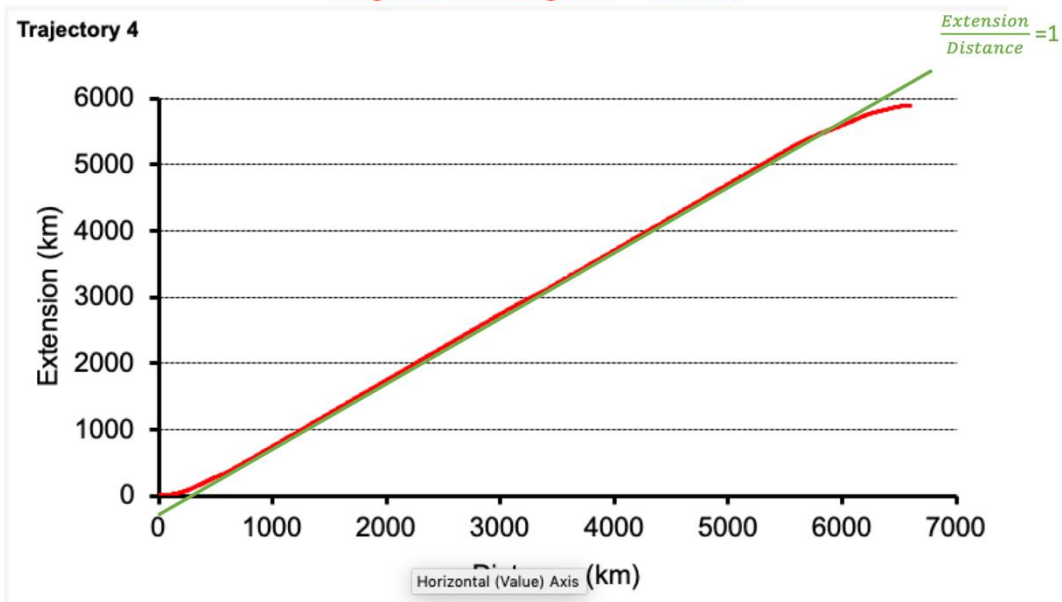


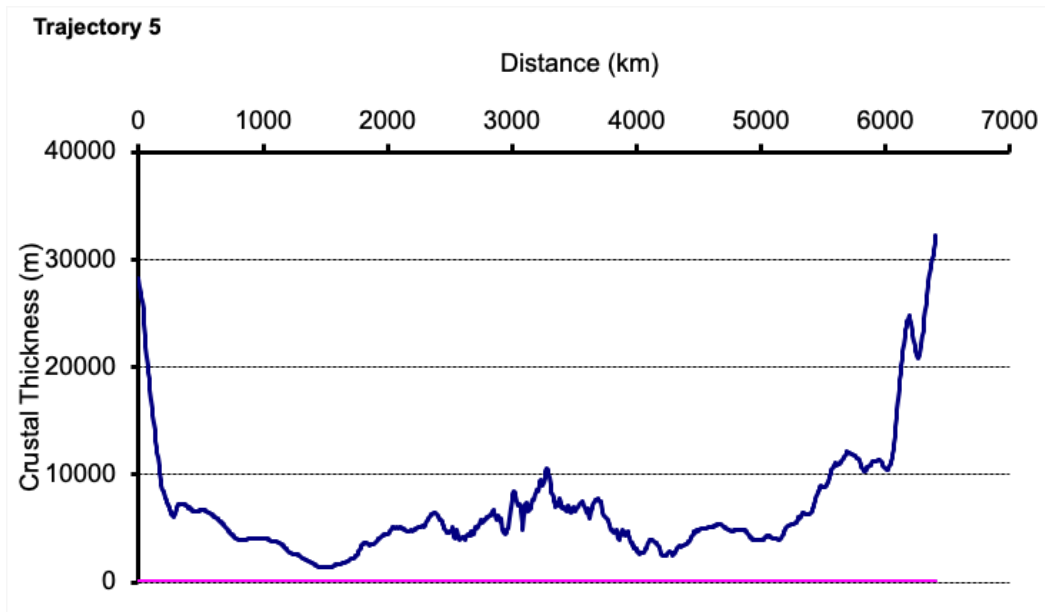
Integration of thinning factor = extension



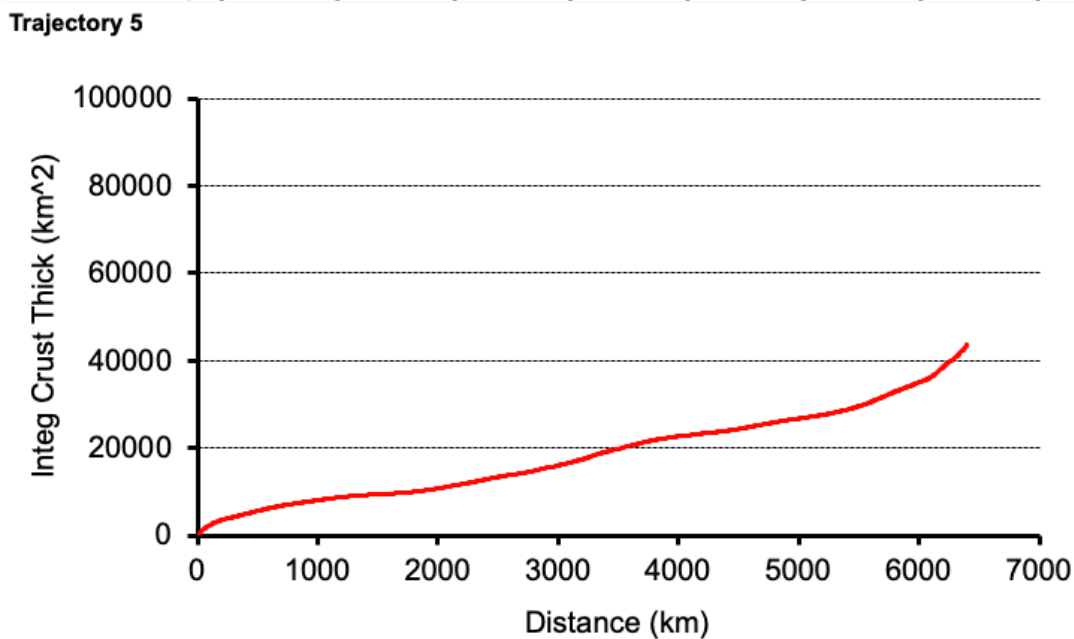
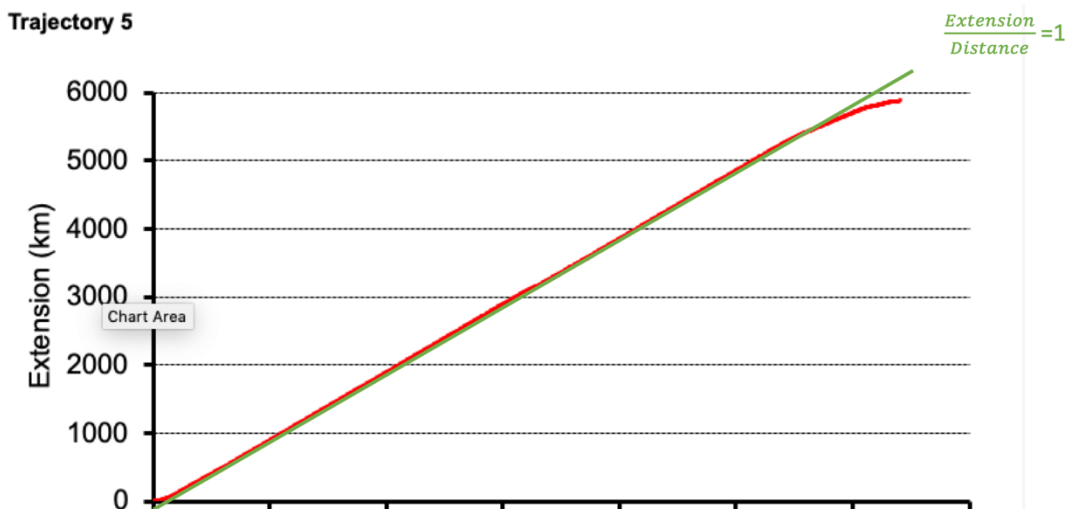


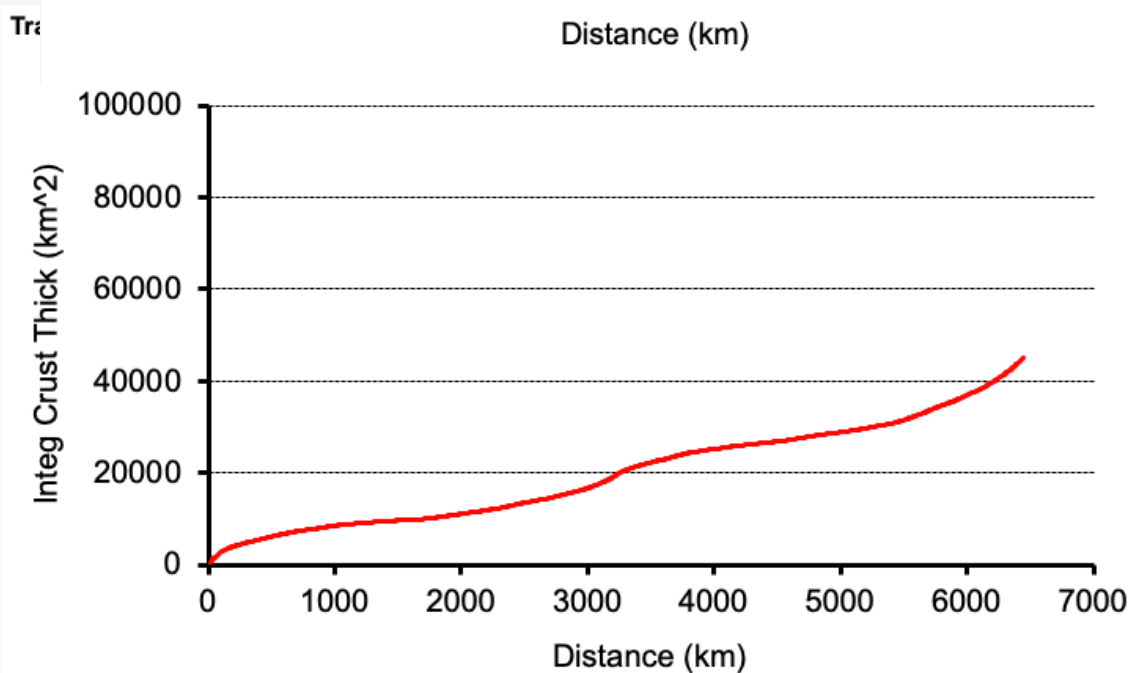
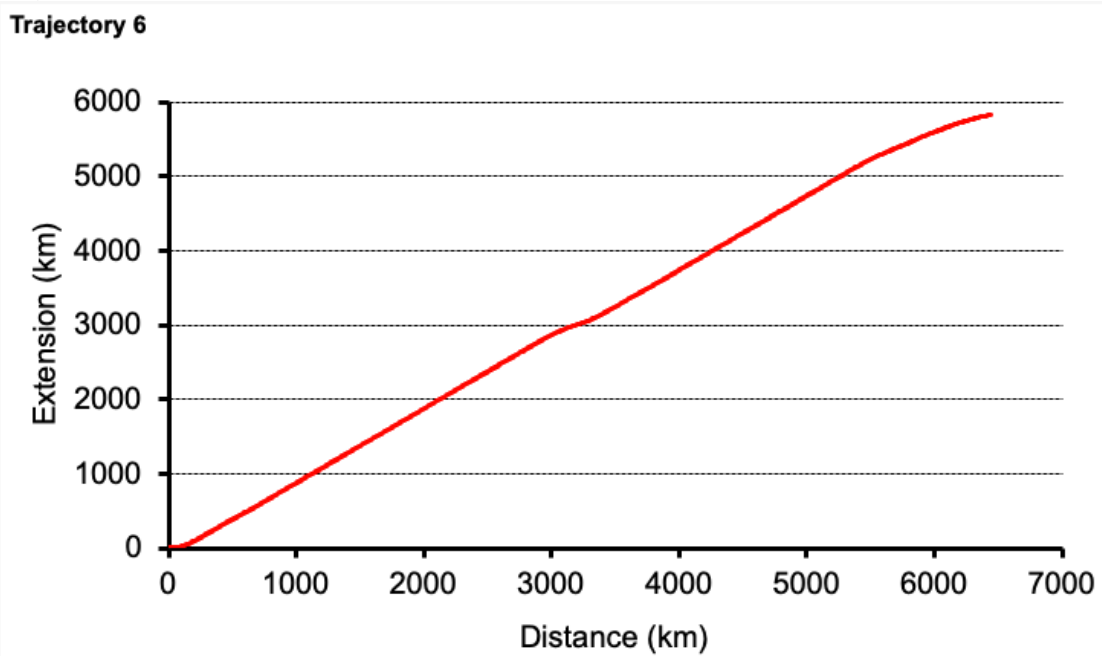
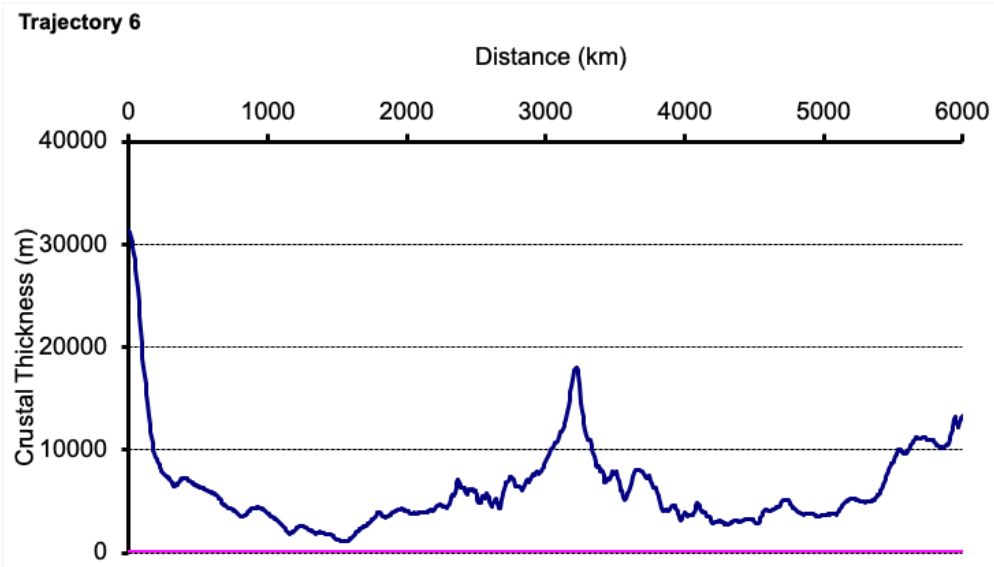
Integration of thinning factor = extension

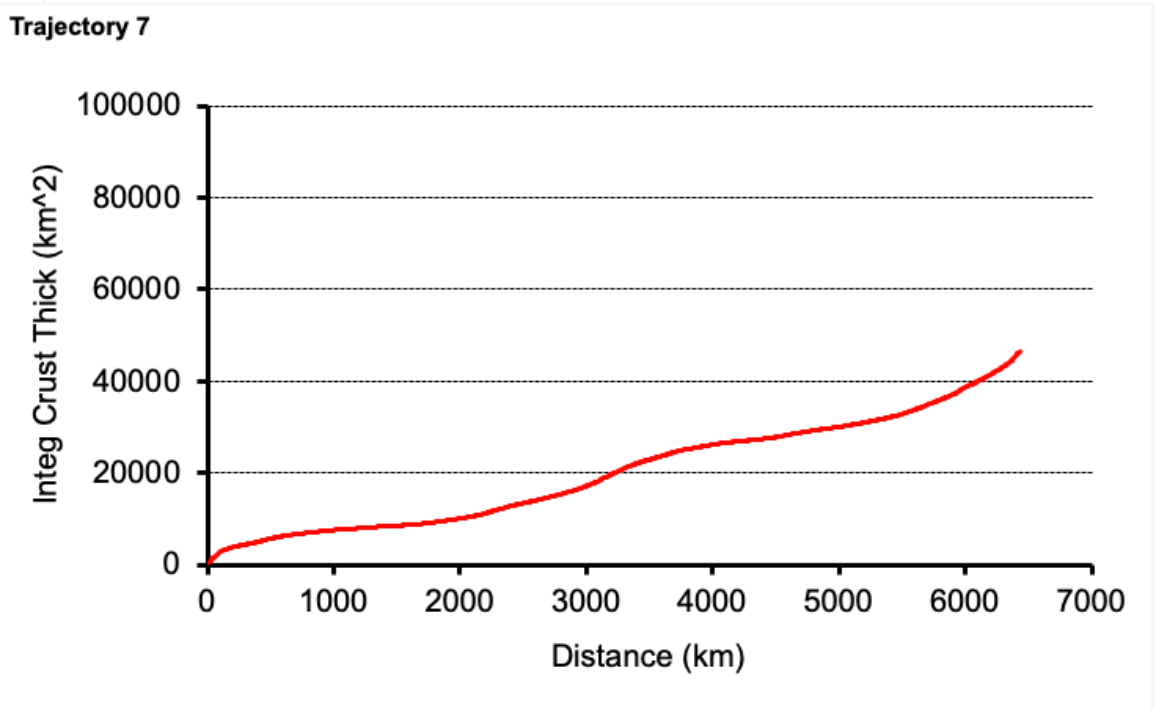
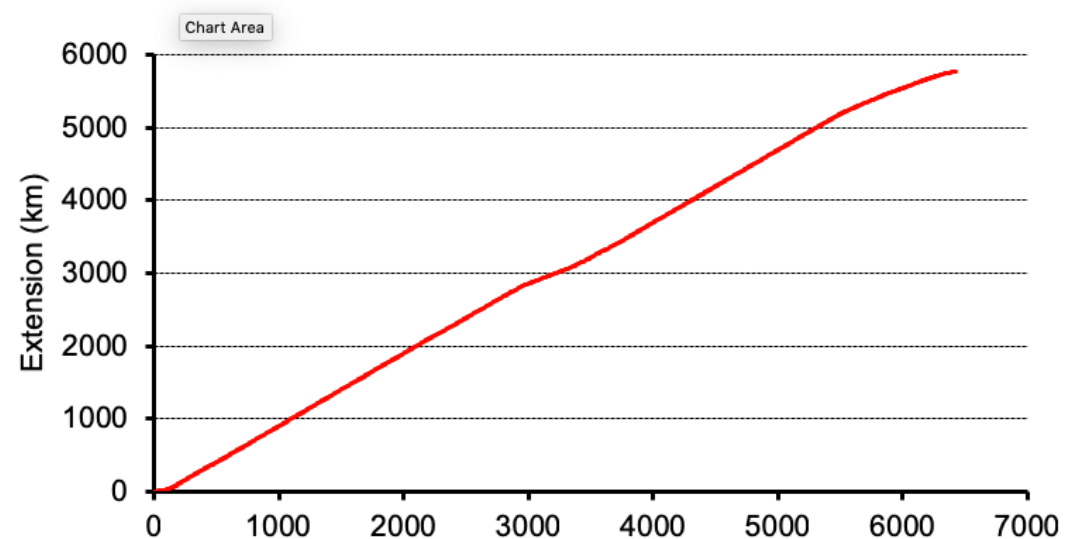
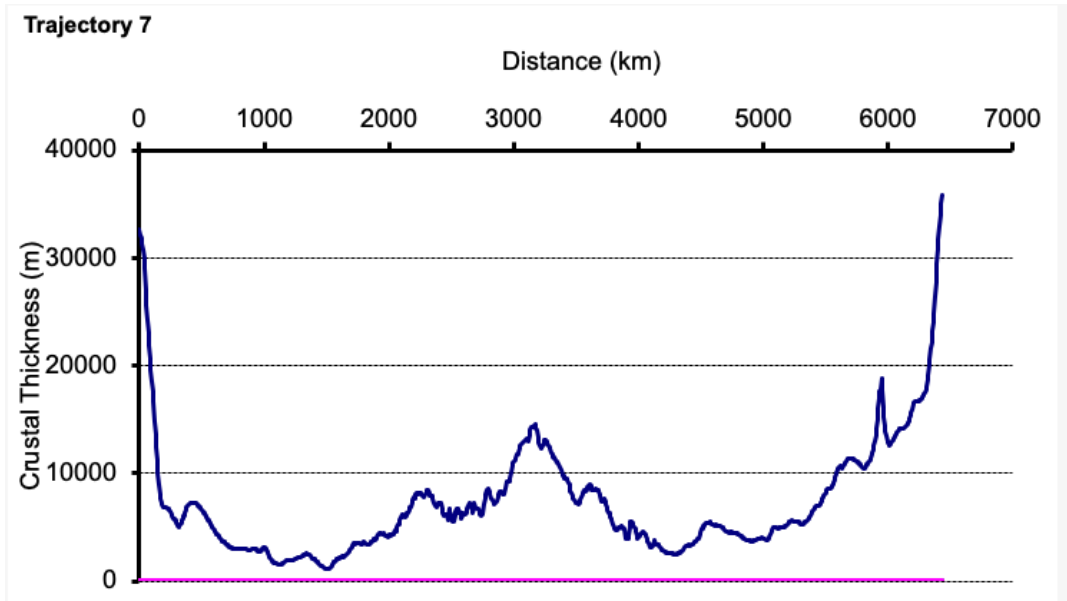


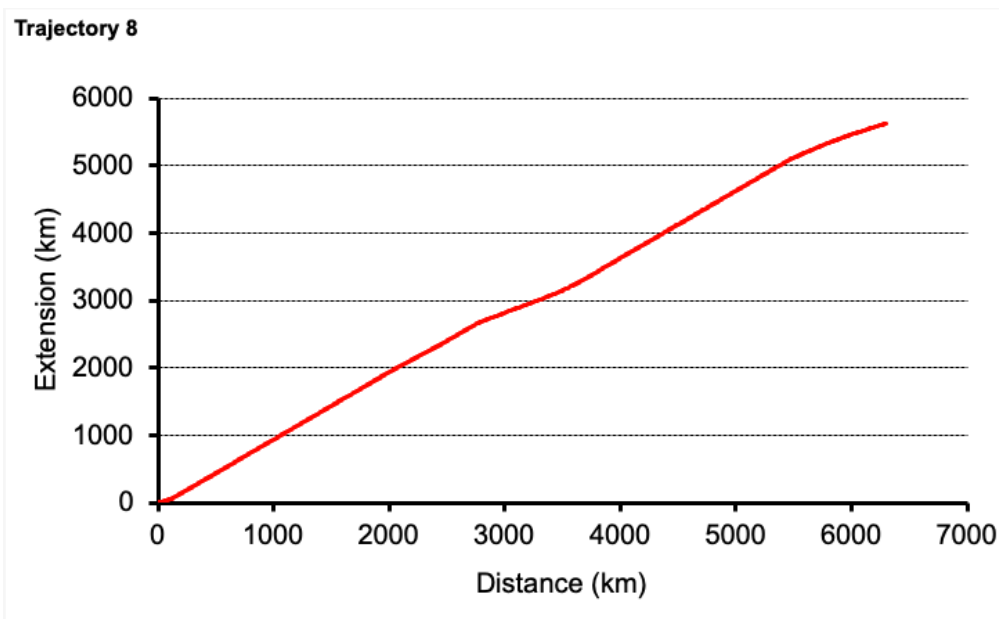
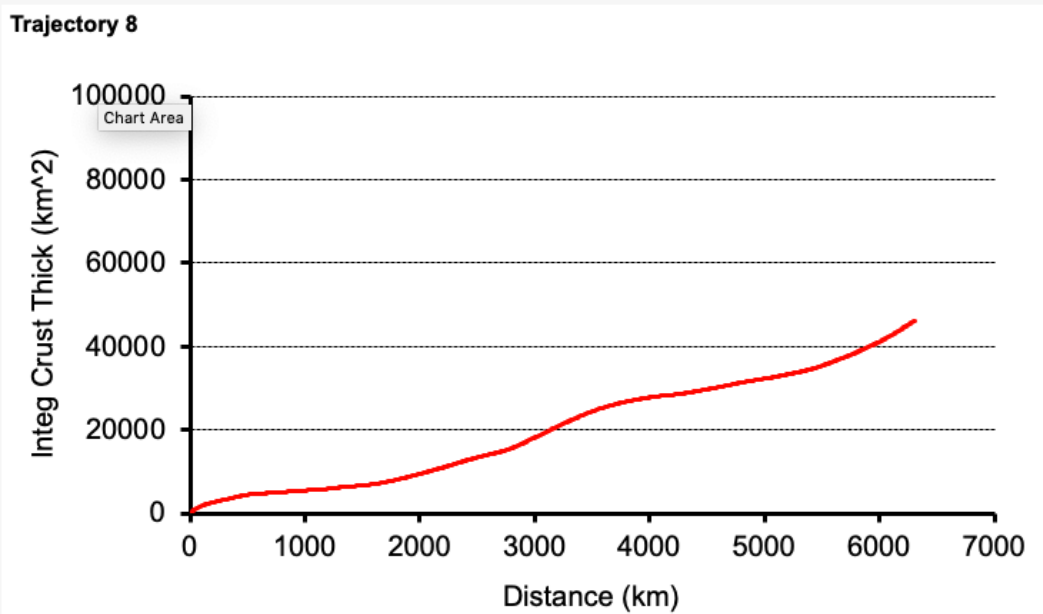
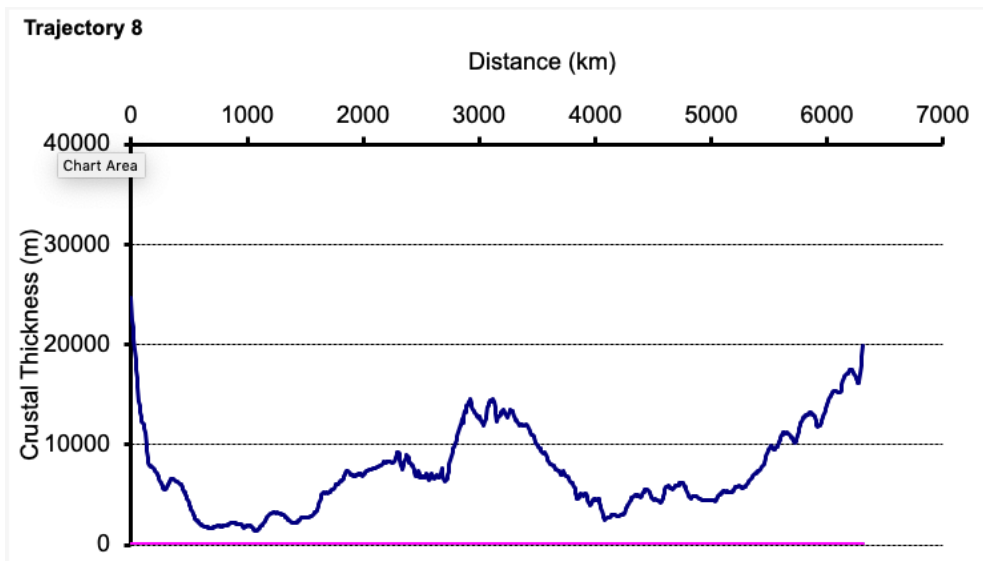


Integration of thinning factor = extension









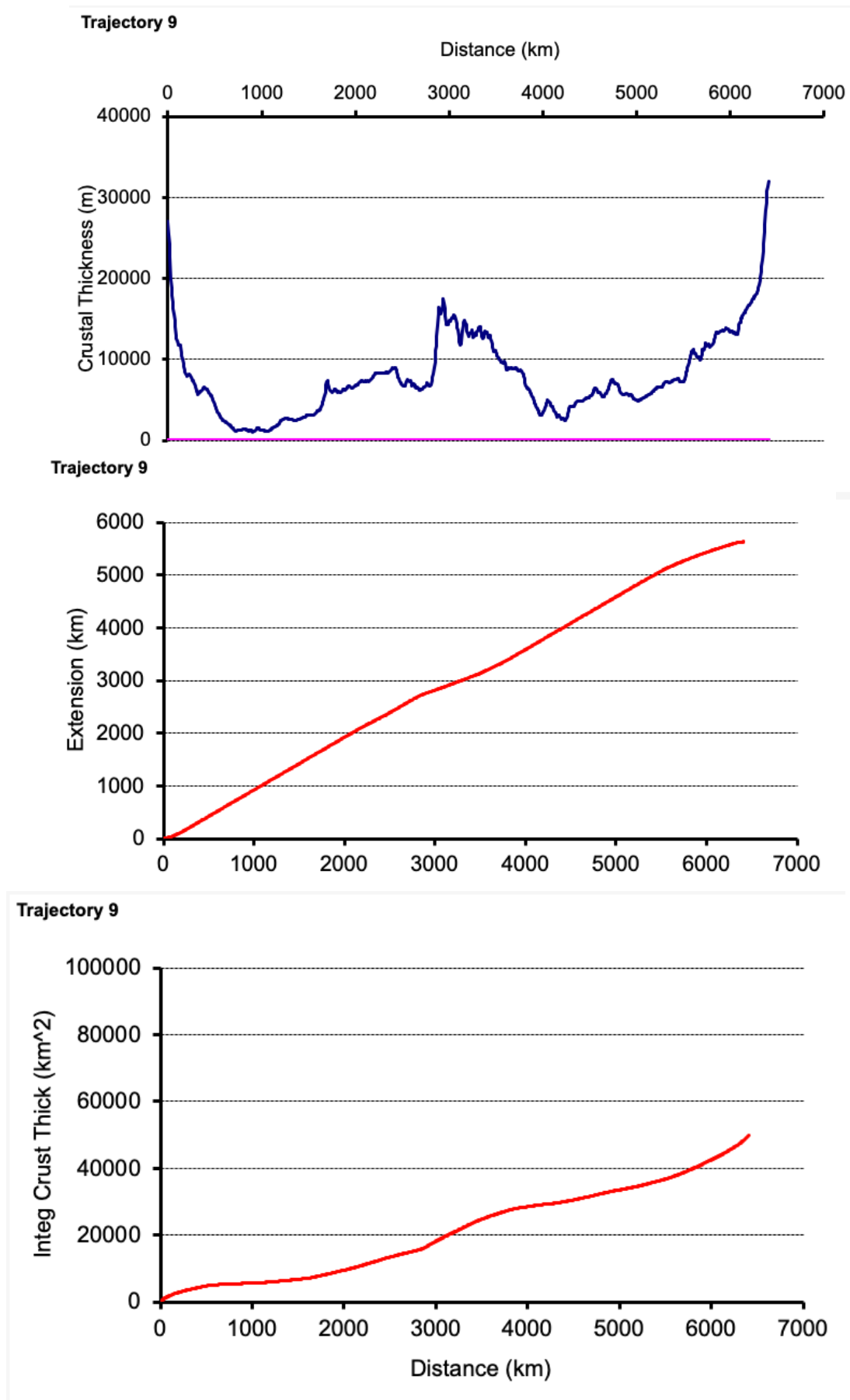


Figure 48: Details of the 9 integrated trajectories using Gplates for the flowlines, and Qgis for the crustal thickness section.

3. Joint inversion

Some results of the joint inversion comparing the gravity inverted Moho with the refraction Moho from the PAMELA line (Moulin et al., 2019) and refraction lines from (Mueller and Jokat, 2017) has been presented (Chapter III). Here I add some results from the

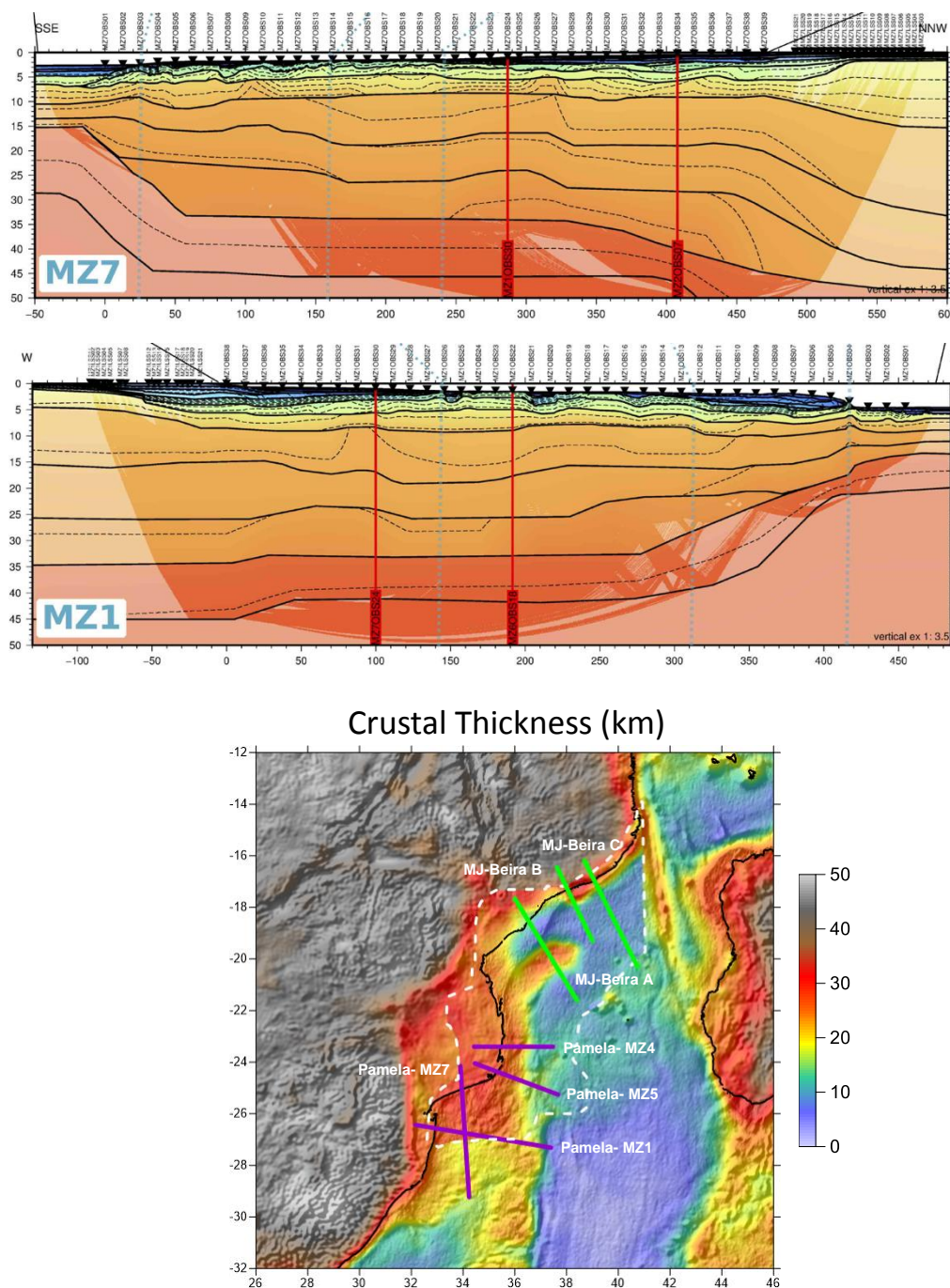
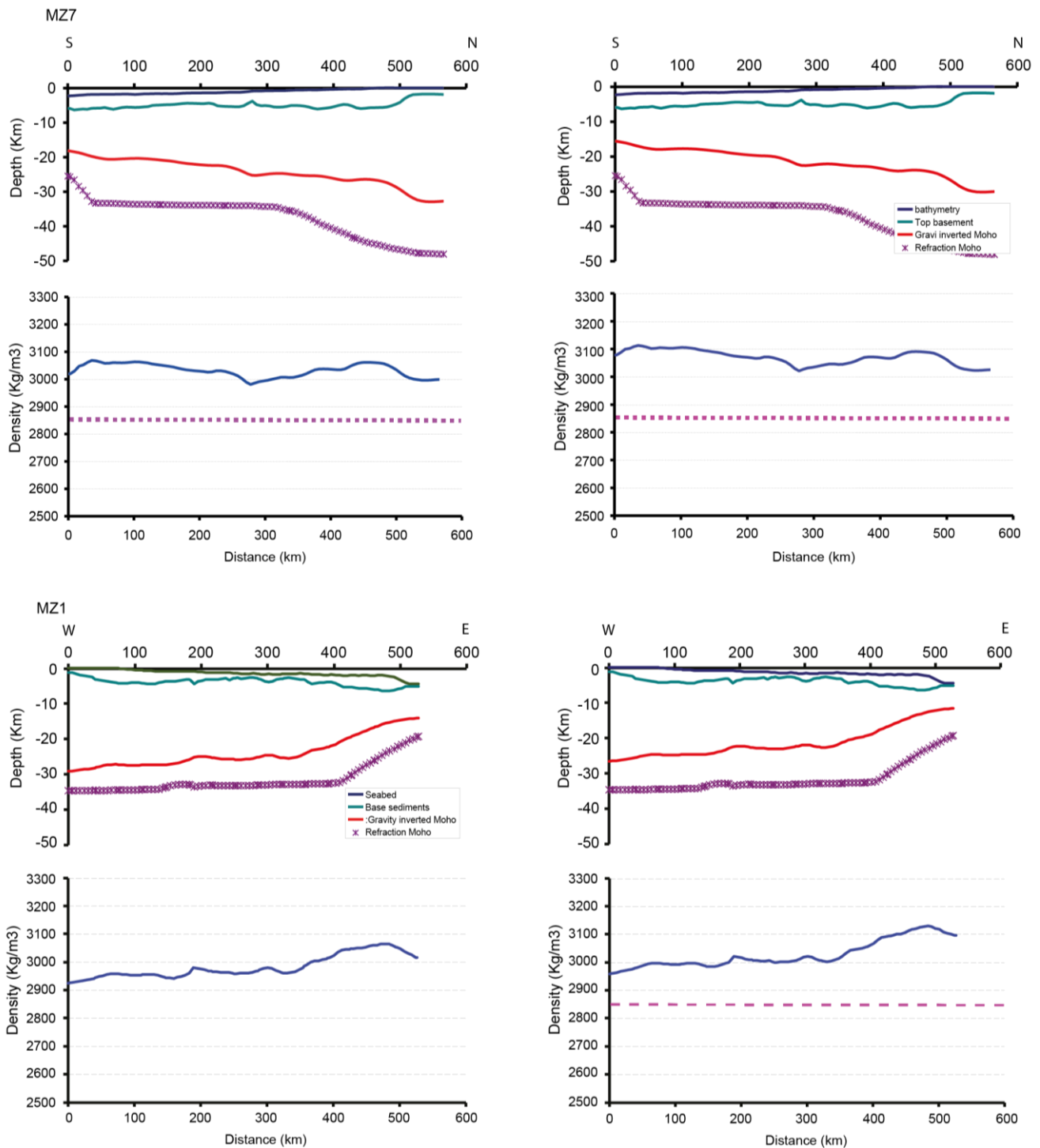


Figure 49: Refraction data from PAMELA acquired by IFREMER in the Northern Natal Valley.



gravity inversion using the Total dataset.

Figure 50: Gravity inversion results using the main interfaces of the refraction data from PAMELA lines. The column on the left shows the results for the model running a 35km Reference Moho Depth (RMD). The column on the right shows the results running a 32.5km RMD. For each joint inversion, we show the crustal densities need in order to fit the gravity Moho with the Moho interface from the refraction line.

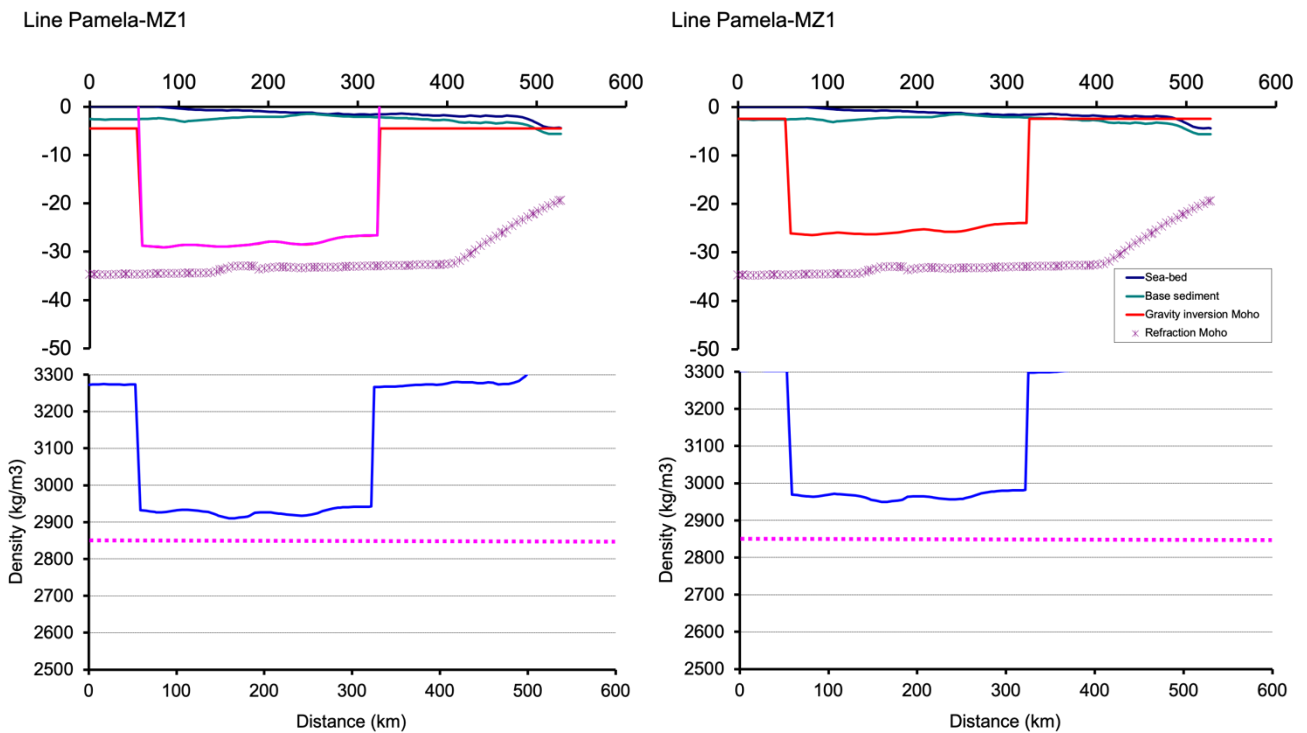


Figure 52: Gravity inversion results using the Total sediment thickness. The column on the left shows the results for the model running a 35km Reference Moho Depth (RMD). The column on the right shows the results running a 32.5km RMD. For each joint inversion, we show the crustal densities need in order to fit the gravity Moho with the Moho interface from the refraction line.

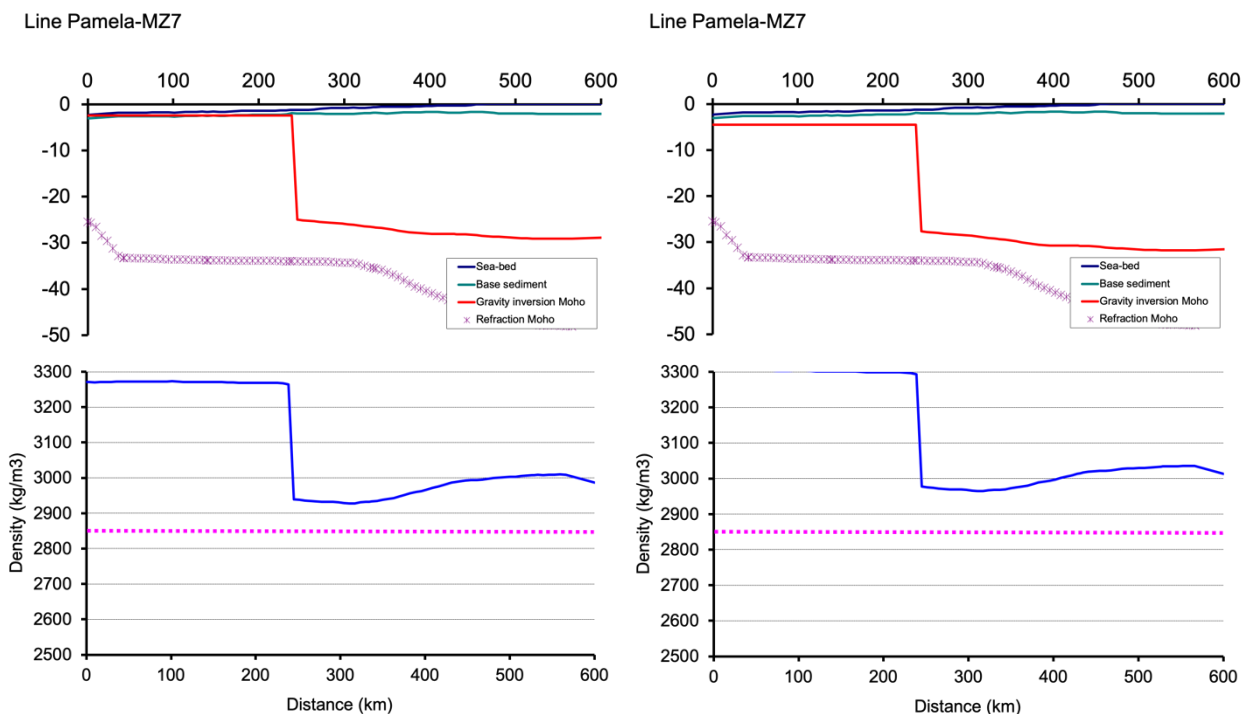


Figure 51: Gravity inversion results using the Total sediment thickness. The column on the left shows the results for the model running a 35km Reference Moho Depth (RMD). The column on the right shows the results running a 32.5km RMD. For each joint inversion, we show the crustal densities need in order to fit the gravity Moho with the Moho interface from the refraction line.

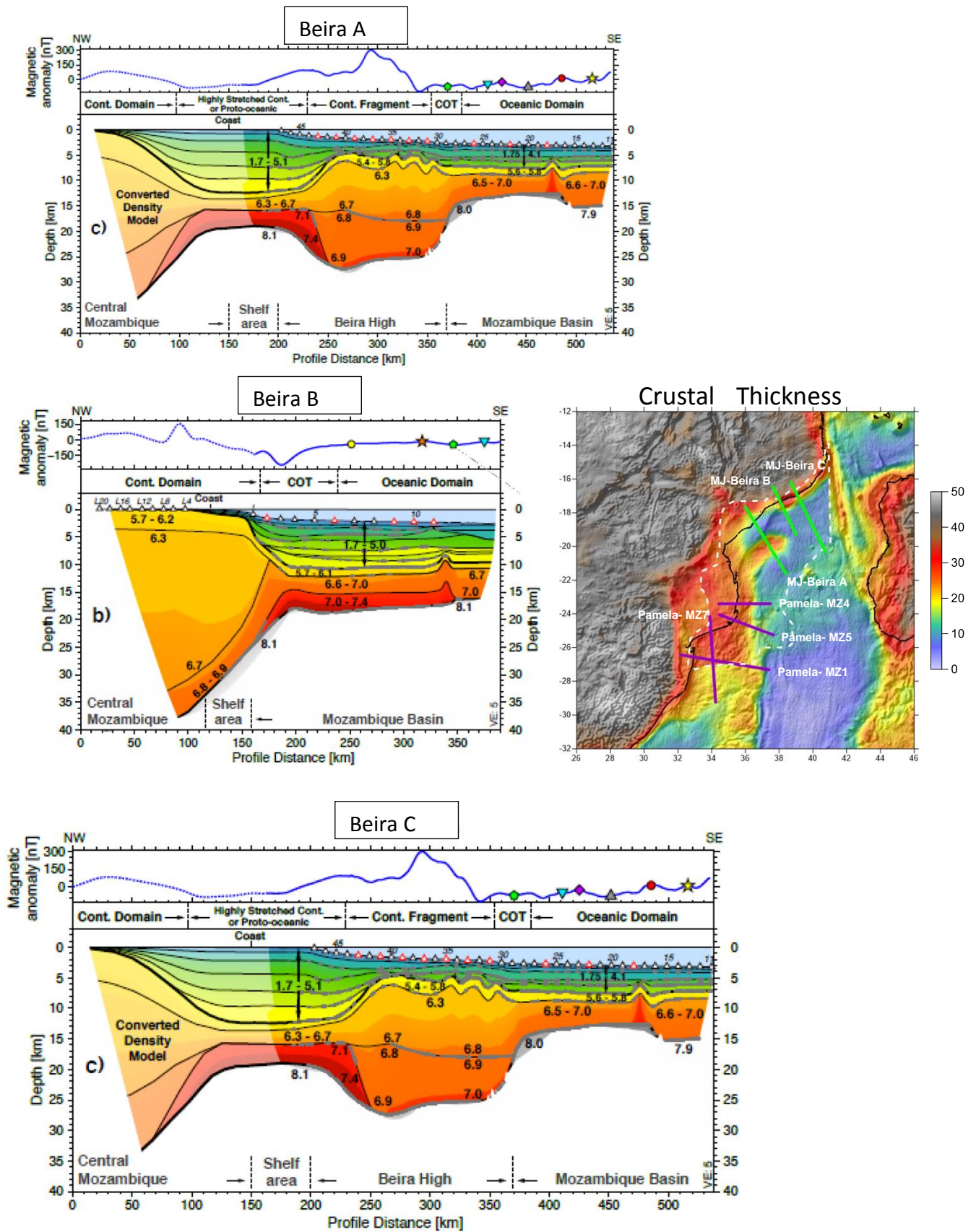
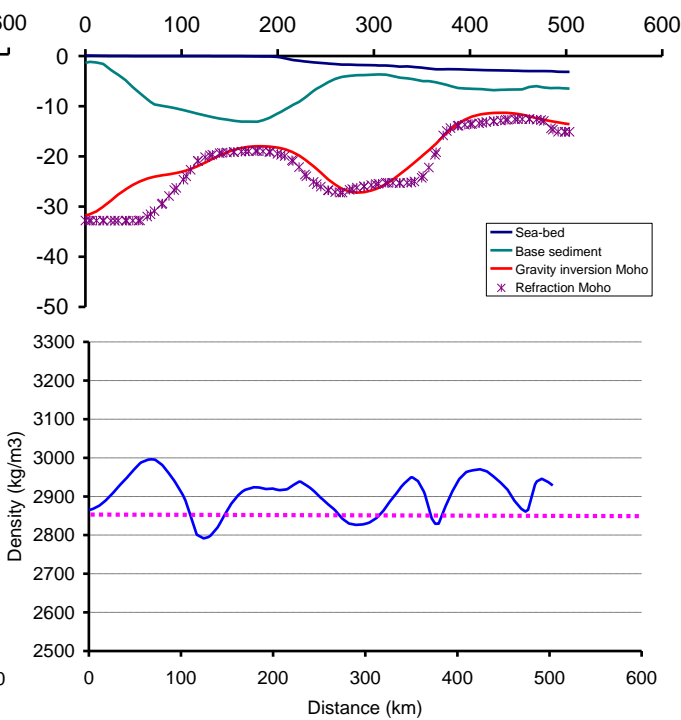
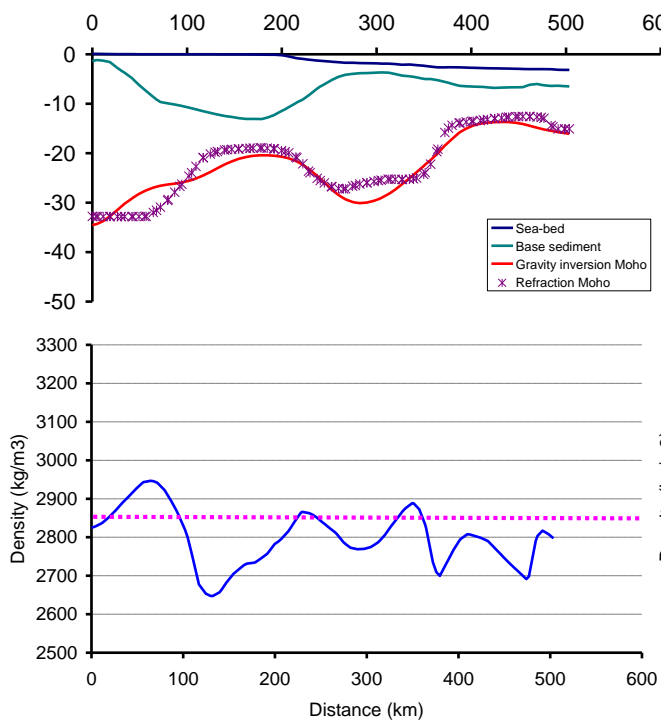


Figure 53: Refraction data from Mueller et al., (2017). Maps shows de location of the lines along the northern Mozambique margin.

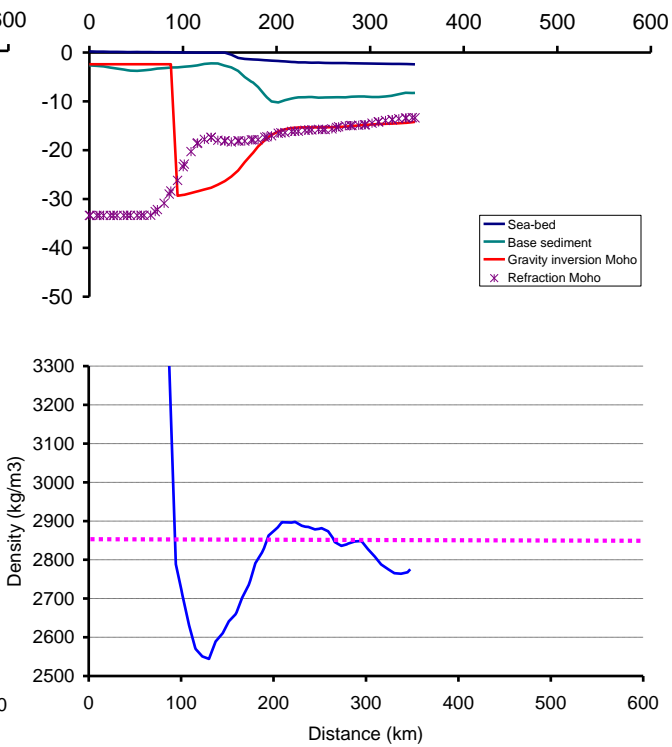
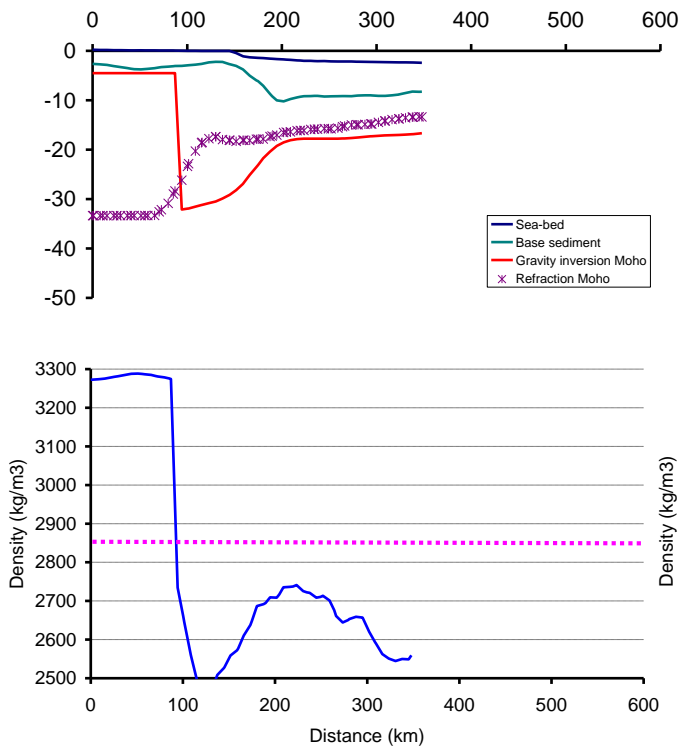
Line MJ-Beira-A

Line MJ-Beira-A



Line MJ-Beira-B

Line MJ-Beira-B



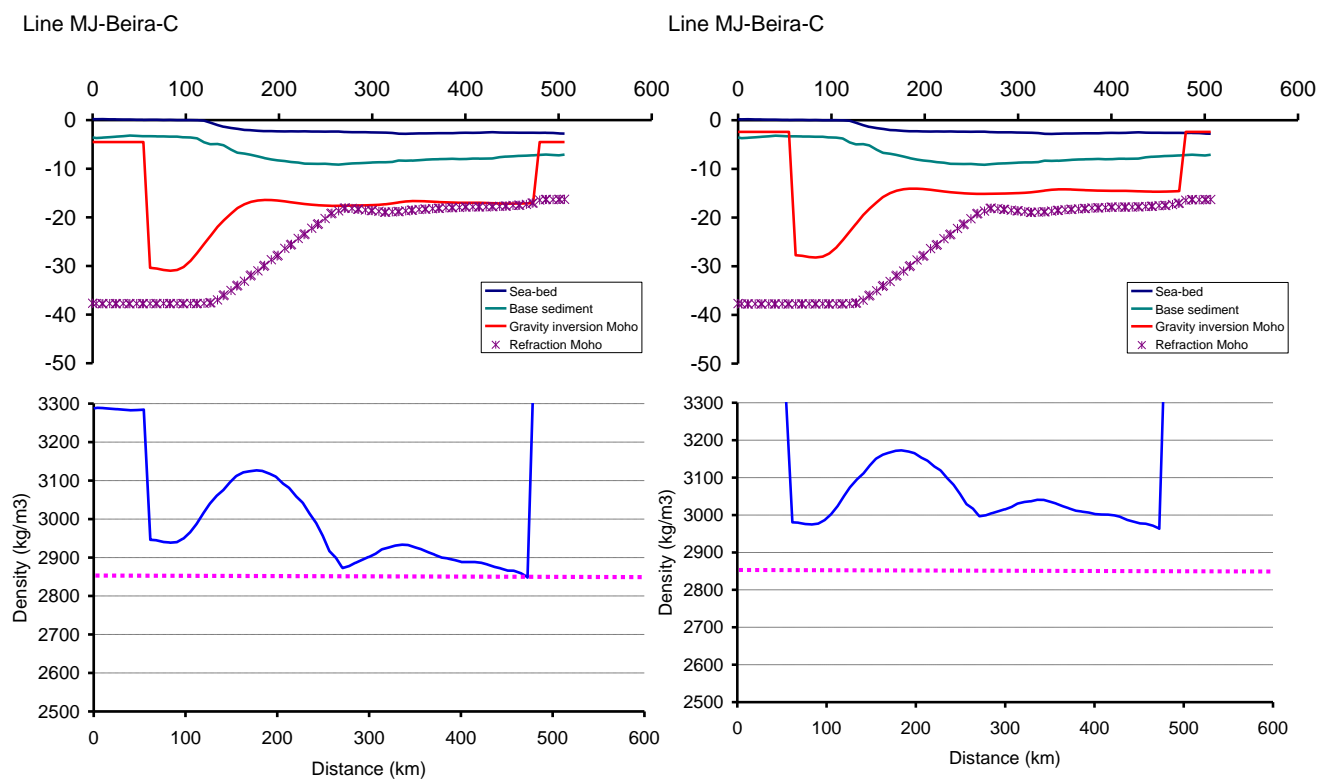
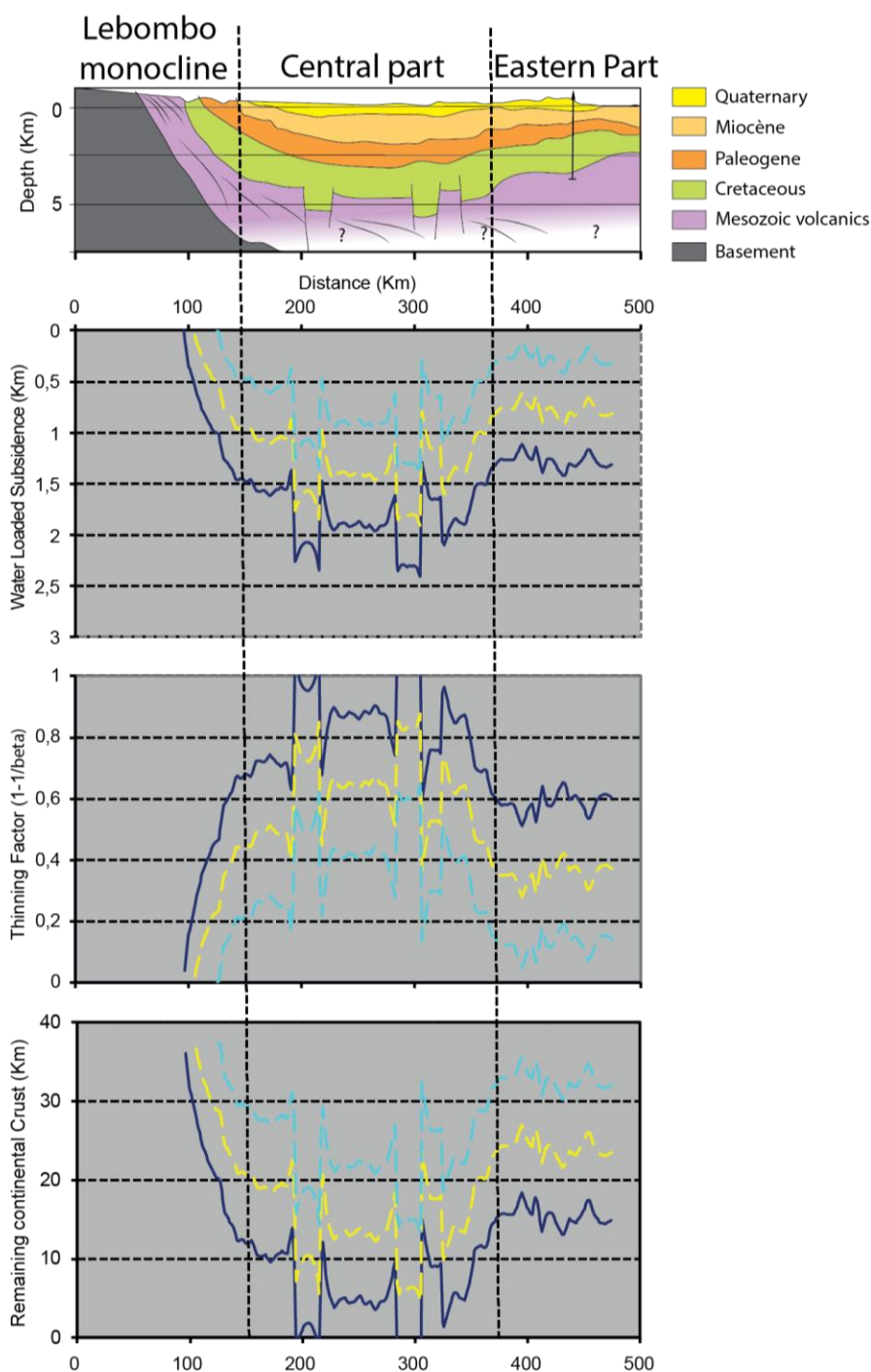


Figure 54: Gravity inversion results using the Total sediment thickness compared with the refraction lines of Mueller et al, (2017). The column on the left shows the results for the model running a 35km Reference Moho Depth (RMD). The column on the right shows the results running a 32.5km RMD. For each joint inversion, we show the crustal densities need in order to fit the gravity Moho with the Moho interface from the refraction line.

4. Subsidence analysis

The subsidence analysis has been performed using Flex-Decomp© software, which is the property of Badleys Geoscience. and allows to observe and estimate the impact of the thermal support during rifting and also allows to test different ages for the basalts observed in the Domo-1 well (see Chapter III). In this section, I gather all the subsidence analysis results.



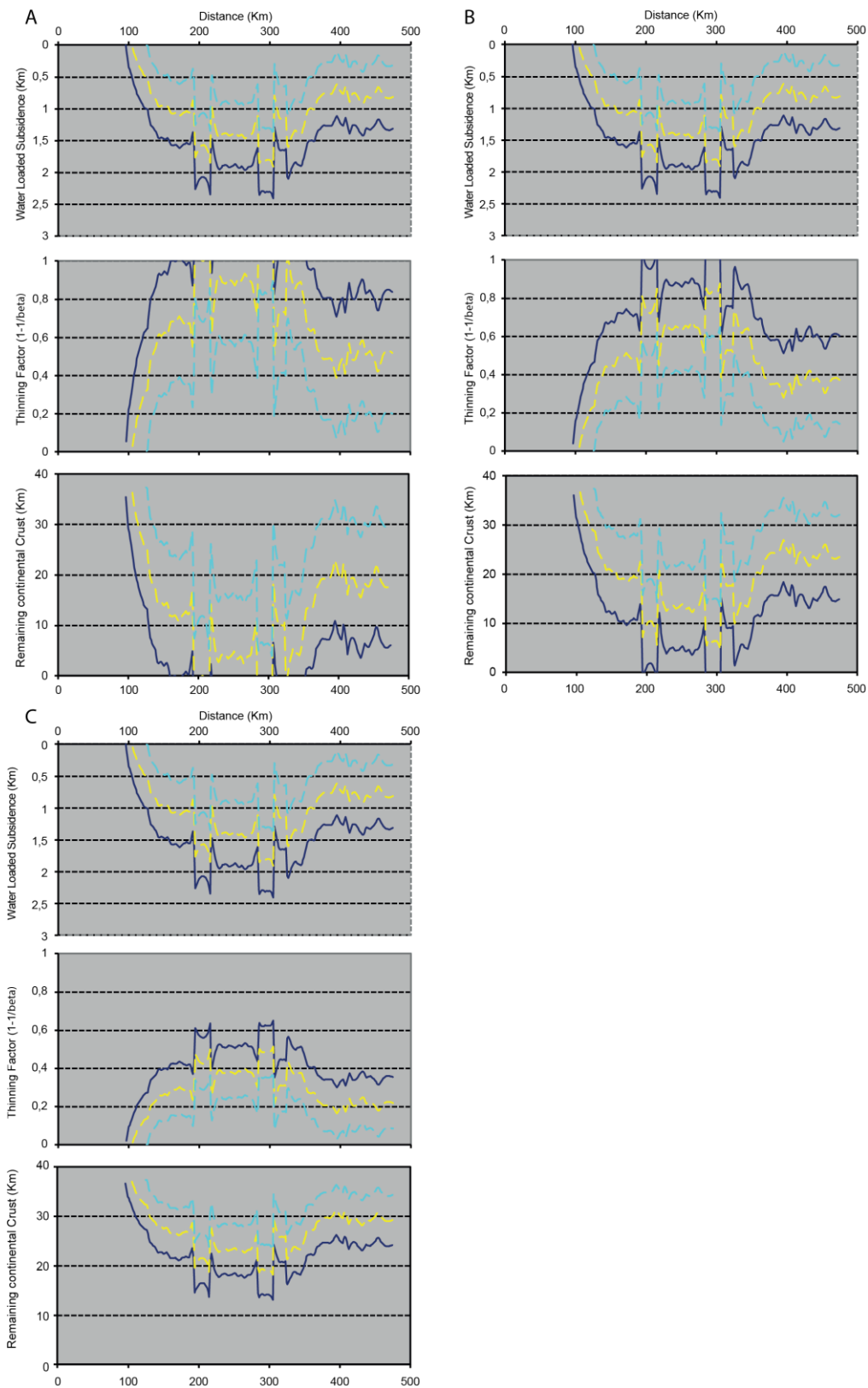


Figure 55: Subsidence analysis of the Mozambique Coastal plains section presented in Davison and Steel, 2018. Here the subsidence analysis is performed using 150Ma for the Central SDR. Dark blue curve represents 0m of dynamic topography at rifting time, Yellow curve represent 500m of dynamic topography, and light blue curve represents 1000m of subsidence. A, B, C represent respectively, 180Ma, 150Ma, 130Ma age of the basalts in the Domo-1 well

5. Restoration Gplates

Gplates is tool which allows to visualize, modify plate kinematics (Müller et al., 2018). In this study, I use Gplates as a tool to compared reconstruction models, analyse end-member scenarios (Chapter II) and trying to find an optimal scenario.

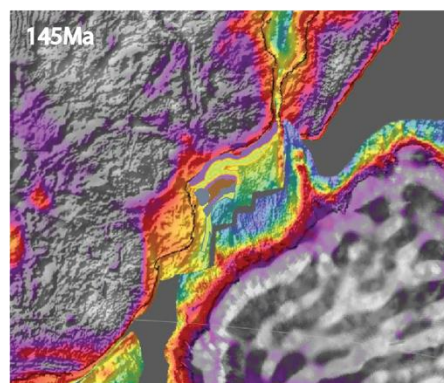
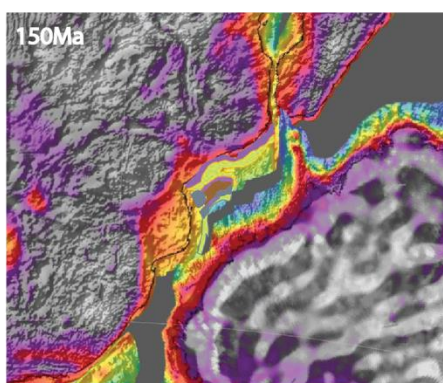
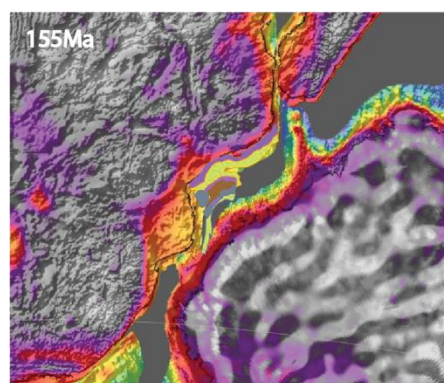
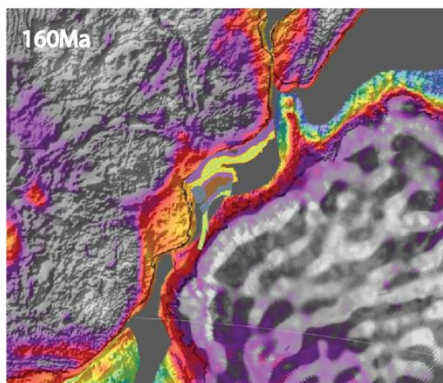
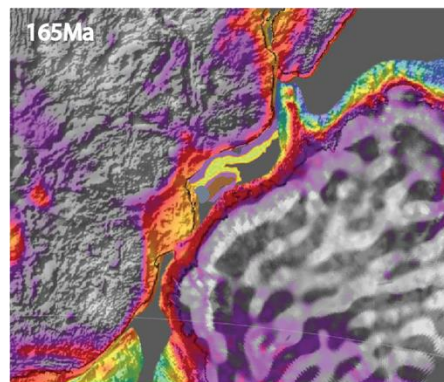
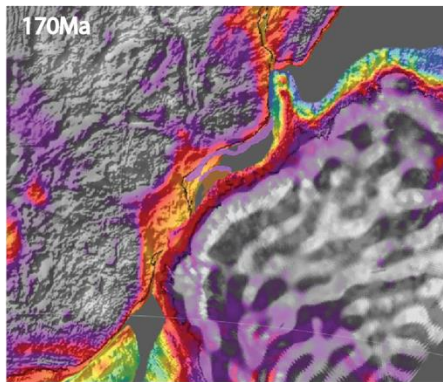
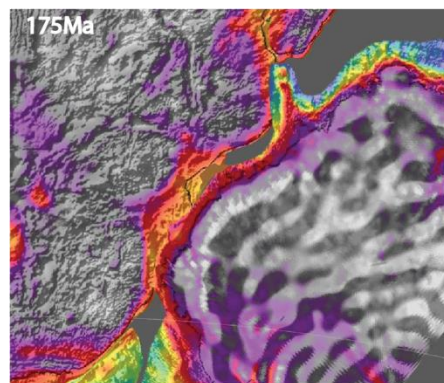
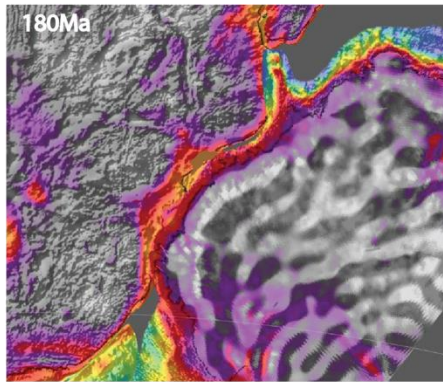
Moving Plate ID	Age (Ma)		Pole Coordinates		Rotation angle (°)		Fixed plate	Reference
102	47.9	53.54	128.4	9.29	301	!GRN-EUR @REF Gaina_+_2009 @DOI"10.1144/0016-76492008-112"		
102	49.7	50.66	127.8	9.56	301	!GRN-EUR @REF Gaina_+_2009 @DOI"10.1144/0016-76492008-112"		
102	53.3	48.67	127.48	10.81	301	!GRN-EUR @REF Barnett-Moore_+_2016 @DOI"10.1111/bre.12214"		
102	55.9	52.02	122.93	12.39	301	!GRN-EUR @REF Barnett-Moore_+_2016 @DOI"10.1111/bre.12214"		
102	56.39	52.11	122.73	12.39	301	!GRN-EUR @REF Barnett-Moore_+_2016 @DOI"10.1111/bre.12214"		

Figure 56: Screenshot of the rotation file used in Gplates. This file lists all the different rotation pole using the Moving Plate ID and the Fixed plate ID, as well as the coordinates of the rotation poles.

During the Ph.D., I tested many models using Gplates to observe the discrepancies, the fits and misfits (Reeves and de Wit, 2000; Leinweber and Jokat, 2012; Reeves, 2014, 2018; Davis et al., 2016; Thompson et al., 2019). The model of Davis presents some interesting geological pin points that I found relevant and it gathered the main geodynamic event of the Gondwana separation. The Table 3 thereafter summarize the changes added to the Davis et al., (2016) model and the Figure 56 illustrates the reconstruction models of this study from 180Ma to 130Ma.

Moving Plate	Age	Latitude	Longitude	Rotation angle	Fixed plate
Antarctica	126.12	-10.64	-26.18	44.84	Africa
	132.13	-11.98	-25.56	48.65	
	135.76	-12.45	-25.34	50.13	
	147.81	-10.11	-28.48	52.62	
	153.71	-9.42	-29.68	54.12	
	182.00	9.74	148.36	-58.03	
	360.00	10.45	148.76	-58.19	
Beira	0.00	90.00	0.00	0.00	Africa
	168.00	90.00	0.00	0.00	
	180.00	-33.62	-66.82	1.87	
	250.00	-14.03	-58.41	2.06	

Table 3: Total rotation poles used in this study



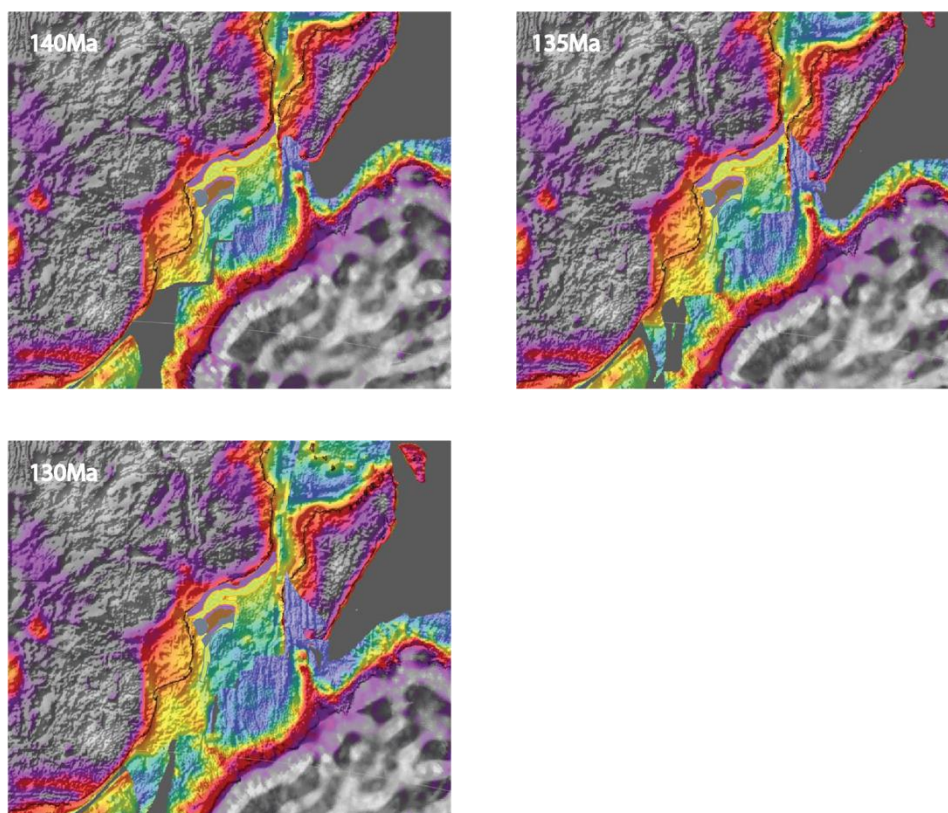


Figure 57: Screenshots from GPlates showing the reconstruction of this study.

Interaction between magmatism and deformation at magma-rich rifted margins: The example of the Mozambique Channel

Bien que l'étude des marges passives ait largement progressée, où, quand, et comment le magma intervient dans la formation de la marge, et comment estimer les volumes relatifs des additions magmatiques par rapport à la croûte originelle restent incompris. Il est cependant nécessaire de comprendre ces interactions pour restaurer le fit initial avant la rupture. Cette étude vise, par l'analyse du système conjugué Mozambique-Antarctique dont l'ouverture est associée à l'action du plume Karoo-Bouvet, à comprendre l'interaction entre magmatisme et déformation dans l'évolution d'un rift.

Une nouvelle méthode de reconstruction cinématique de scénarios opposés en termes de budget magmatique permet de mettre en évidence dans les plaines côtières du Mozambique une zone de croûte hybride : une croûte continentale amincie qui est lourdement affectée par du magmatisme syn-extension qui remplit l'espace d'accommodation créé.

Cette croûte hybride est analysée à l'aide de méthodes géophysiques : inversion gravimétrique, comparaison du Moho issu de l'inversion gravimétrique et du Moho de données de réfraction, et analyse de subsidence. Ainsi, la croûte hybride des plaines côtières du Mozambique vérifie les 3 caractéristiques majeures proposées pour un modèle de croûte hybride : 1) toit du socle plat, non-structuré par des failles, parallèle au Moho, 2) une densité crustale élevée à cause des additions magmatiques, et 3) une subsidence thermique significative due à la résorption du plume.

Il est donc important de comprendre que le timing du magmatisme ainsi que son budget sont nécessaires pour caractériser une marge passive et en comprendre son évolution. Ainsi une nouvelle classification de marges passives est proposée, permettant de déterminer ces deux paramètres et basée sur l'architecture au premier ordre de la croûte.

Mots clés : Marge riche en magma, Mozambique, Antarctique, Budget et timing magmatisme, Reconstruction cinématique

Although the understanding of rifted margins has improved, when, where and how magmatism forms during the evolution of the margin and how to assess the relative volume of the magmatic addition compared to the inherited crust are still poorly understood. Integrating these interactions is essential to restore these systems to the pre-break-up stage. This study aims to understand these interactions and propose methods to evaluate the magmatic budget and timing through the analysis of the Mozambique-Antarctica conjugated rift system.

A new method consisting in restoring end-member scenarios is developed to estimate magmatic budget in domains where the seismic interpretation is hindered by high magmatic budget. This method highlight that the Mozambique Coastal Plains and Beira High are floored by hybrid crust (i.e, thinned inherited continental crust with syn-tectonic magmatic additions, which fill up the accommodation space).

This hybrid crust is analysed through geophysical methods comprising gravity inversion, crustal density analysis and subsidence analysis. The Mozambique Coastal Plains unify the 3 main characteristics of hybrid crust, which are: 1) flat, unfaulted, top basement parallel to Moho, 2) high-density crust due to significant magmatic additions, and 3) high post-rift subsidence due to thermal equilibration and plume collapse.

Integrating the budget and also the timing of magmatic processes are required to characterize and understand the evolution of a rifted margin. Therefore, a new classification is proposed linking the first order crustal shape to the magmatic budget and timing.

Keywords: magma-rich margin, Mozambique Antarctica, timing and budget of magmatism, tight fit restoration