ALFRED-WEGENER-INSTITUT
HELMHOLTZ-ZENTRUM FÜR POLAR-
UND MEERESFORSCHUNG

Universität Bremen

Sedimentation history and geodynamic evolution of the Mozambique Basin using seismic data

Dissertation

zur Erlangung des Doktorgrades
der Naturwissenschaften
-Doctor rerum naturalium-
(Dr. rer. Nat.)
am Fachbereich Geowissenschaften
der Universität Bremen

vorgelegt von
Jude A. Castelino

Bremen, June 2016

Gutachter / Reviewer:

Prof. Dr. Wilfried Jokat

Prof. Dr. Katrin Huhn-Frehers

Tag des Promotionskolloquiums/ Date of Colloquium:
20 October, 2016

Weitere Mitglieder der Prüfungskomission/
Additional members of the examination board:

Prof. Dr. Marta Pérez -Gussinyé
Prof. Dr. Wolfgang Bach
Dr. Stefan Wenau
Janneke Hippen

Declaration

Name: Jude A. Castelino

Address: Ostertorsteinweg 105
28203, Bremen
Germany

Herewith I declare that

I. This document and the accompanying data has been composed by myself, and describes my own work

II. I have not used any sources or additives other than those stated, and

III. Material from the published or unpublished work of others, which is referred to in this dissertation, is credited to the authors(s)

IV. This work has not been submitted for any other degree

Bremen, 27 June 2016

………………………………

Jude A. Castelino

Abstract

Continental break-up and collision and the opening and closing of ocean basin constitute the integral part of the Wilson cycle that constantly recycles the Earth's crust. The initial dispersal of the last supercontinent Gondwana into east and west Gondwana resulted in the formation of the several ocean basins along the margins. The oldest amongst the basins along the West Gondwana margin -- presently the Eastern Africa passive margin -- are the Somali and Mozambique basins.

The submarine morphological features of passive margins are dominated by downslope and along slope processes that are directly or indirectly controlled by tectonic, oceanic and climatic settings. The Mozambique Basin hosts a thick and continuous sequence of sediment archive from the Jurassic separation of Antarctica from Africa but despite its economic and geological significance, the region continues to remain poorly studied.

This cumulative dissertation focuses on the evolution of the Mozambique Basin and its transition from a rift basin to a passive margin basin. 2200 km of seismic profiles and bathymetry data acquired in 2007 have been used to study the controls on sediment architecture and dispersal of sediments in the basin along the Mozambican continental margin. Additionally, palaeobathymetry models of the Africa-Antarctic Corridor using "backstripping" technique and plate kinematics augment our knowledge of the basin.

The palaeobathymetry models show topographic highs along the edge of the basin namely, the continental margins, Mozambique, Gunnerus, Astrid ridges enclosed the basin preventing any bottom circulation until the Late Cretaceous. High sediment accumulation rates coupled with a euxinic setting in a rapidly subsiding basin results the formation of shale layers interbedded with turbidite layers. The present-day 1800 km long and 400 km wide Mozambique Fan is spread out in the Mozambique Channel. Local sea-level change and increased sediment influx due to tectonic activity into the basin from the Zambezi in Late Cretaceous times resulted in the formation of an elongated submarine fan lobe into the Mozambique Channel north of Beira High. Strong north-south bottom currents commenced within the channel in Late Cretaceous times, forcing the aggradation of sediments on the southern flank of the lobe until the

Eocene. In addition, we observe several current-controlled sediment deposits in the deeper basin that are influenced by north-south bottom currents.

The taphrogenesis along the Mozambique margin ensured that turbidite systems continued to feed the basin after the mid-Oligocene marine regression with a large Channel-levee complex over Beira High supplying sediments from the southwest until Miocene times. Since the Miocene, sediments bypassed the shelf and upper fan region through the Zambezi Valley system directly into the Zambezi Channel.

The palaeobathymetry models reveal a previously undocumented uplift in the Mozambique Basin ranging up to 1300 m, that cannot be explained by mantle convection or plumes alone as on the neighbouring African continent. Instead thickening of the oceanic crust due to underplating is a more reasonable assumption when the basin passed over the Quathlamba Hotspot during Early Paleogene that also produced Bassas Da India and Isle de Europa. Both conjugate margins display flexure over half-wavelengths of ~60-80 km landwards and an amplitudes of 1500 m. Isolated crustal fragments of transitional or continental composition near the margin, including Beira High and Gunnerus Ridge subside in similar to adjoining oceanic crust.

Overall, the new discoveries in this thesis make significant contributions to the understanding of passive margin development off Mozambique.

Zusammenfassung

Der Aufbruch und die Kollision von Kontinenten sowie die Bildung und Subduktion von Ozeanbecken bilden einen wesentlichen Teil des Wilson-Zyklus. Der Aufbruch des letzten Superkontinents Gondwana in Ost- und West Gondwana führte zur Bildung mehrerer Ozeanbecken entlang der Bruchstelle. Die ältesten dieser Becken, das Somali und das Mosambik Becken, liegen entlang des passiven Kontinentalrandes West Gondwanas.

Passive Kontinentalränder sind die untermeerische Sockel der Kontinente, durch hangabwärts oder hangparallel gerichtete Sedimentationsprozesse geprägt werden. Unterschiedliche tektonischem ozeanographische und klimatische Faktoren beeinflussen die Sedimentation an passiven Kontinentalränder sowohl direkt als auch indirekt. Im Mosambik Becken finden sich mächtige, kontinuierliche Sedimentabfolgen, welche bis zurück zur jurassischen Aufbrechen zwischen Afrika und der Antarktis reichen. Trotz seiner wirtschaftlichen und geologischen Bedeutung ist das Sedimentarchiv des Mosambik Beckens bis heute kaum erforscht.

Als Datenbasis, im Mosambik Becken und an der Übergangszone vom Becken zum passiven Kontinentalrand an der mosambikanischen Küste dienen insgesamt 2200 km lange seismische Profile und bathymetrische Daten , welche im Jahr 2007 erfassten wurden. Das wesentliche Ziel der Arbeit ist es die Prozesse zu untersuchen welche die Sediment- Aufbau und Verteilung im Mosambik Becken kontrollieren. Zusätzlich wurden mithilfe der Backstripping-Methode palaeobathymetrische Modelle des Afrika-Antarktis-Korridors erstellt welche unser Verständnis über das Mosambik Becken erweitern.

Die paläobathymetrischen Modelle zeigen dass das Mosambik Becken bis zum Zeitalter der Kreide von den Kontinentaländern west Gondwanas mit Mosambik auf der afrikanischen Seite und, dem Gunnerus Rücken und dem Astrid Rücken auf der antarktischen Seite umschlossen war. Deshalb lag bis dahin keine Tiefenwasserzirkulation im Becken vor. Hohe Sedimentationsraten in der Kombination mit einem Euxinisches Milieu führten in dem sich rasch absenkenden Mosambik Becken zur Bildung einer wechselnden Abfolge aus Tonschiefer und Turbiditlagen. Heute finden wir einen 1800 km langen und 400 km breiten Sedimentfächer in der Straße von Mosambik. Lokale Meeresspiegeländerungen und erhöhter Sedimenteintrag in späten

Kreidezeit führten zur Bildung eines länglichen submarinen Sedimentfächers, der nördlich des Beira Hochs in die Straße von Mosambik reicht. Das Einsetzen starker Nord-Süd gerichteter Bodenströmungen führten zur Akkumulation von Sedimenten an der südlichen Flanke des Lobus zwischen der späten Kreidezeit und dem Eozän. Verschiedene strömungsbeeinflusste Sedimentablagerungen im tiefen Teil des Mosambik Becken deuten auch auf diese Nord-Süd gerichtete Bodenströmung hin.

Die Taphrogenese entlang des Mosambik Kontinentalrandes führte dazu dass, auch nach der Regression im mittleren Oligozän, Turbidite Ströme durch ein ausgeprägtes Channel-Levee System bis ins Miozän über dem Beira High aus dem Südwesten in das Mosambik Becken gelangten. Seit dem Miozän verläuft der Transport der Sediment durch das submarinen Zambesi Canyon System und wird damit den Schelf und die Region des oberen Zambesi Fächers.

Das palaeobathymetrie model zeigt eine lokaler Hebung von bis zu 1300 m innerhalb des Beckens, welche sich nicht alleine durch Konvektion oder Plumes im Erdmantel erklären lassen. Stattdessen lässt sich die lokale Hebung besser mit magmatischen Underplating unter lokalen ozeanischen Kruste, gefüttert durch den Quathlamba Hotspot, der auch die Inseln Bassas Da India und Isle de Europa hervorgebracht hat, erklären. Die Kontinentalränder beiderseits des Mosambik Becks zeigen eine Flexur der Wellenlänge von ~60-80 km landeinwärts und einer Amplitude von 1500 m. Fragmente von umstrittener oder kontinental Krustenzusammensetzung in der Nähe der Kontinentalränder, einschließlich des Beira Highs und des Gunnerus Rückens sinken wie nebenstehend Ozeankruste ab.

Table of Contents

List of figures

List of abbreviation

AAC: African-Antarctic Corridor
ALS: Acquisition Line System
ATCM : Antarctic Treaty Consultative Meeting
AWI: Alfred Wegener Institute – Hemholtz Centre – For Polar and Marine Research
BGR: Bundesministerium für Geowissenschaft und Rohstoff
CDP: Common Depth Point
COB: Continent Ocean Boundary
COTZ: Continent Ocean Transition Zone
FD: Finite Difference
GDH1: Global Depth and Heat flow model
GEBCO: General Bathymetric Chart of the Oceans
GMT: Generic Mapping Tools
GPS: Global Positioning System
IFREMER: I*nstitut français de recherche pour l'exploitation de la mer*
IPEV: Institut polaire français Paul-Emile Victor
MBES: Multibeam Echo Sounding
MBSU: Mozambique Basin Seismic Unit
MCS: Multi-channel seismic
MoBaMaSiS: Mozambique Basin Marine Seismic Survey
NMO: Normal Move-Out
OVC: Over-correction
PMGE: Polar Marine Geosurvey Expedition
PSM: Parson Slater Model
RLS: Riiser-Larsen Sea
SCAR: Scientific Committee on Antarctic Research
SDLS: Antarctic Seismic Data Library
SRMA: Surface related multiple attenuation
ZDD: Zambezi Delta Depression

Chapter 1: Introduction and Motivation

1.1. What are passive continental margin basins?

Passive continental margins are transition zones between continental and oceanic lithosphere that are located within a plate boundary where tectonic activity has ceased (Figure 1.1) unlike its "active" counterpart, which is located at the plate edge. Many passive margins are formed by thermal contraction following rifting that accompanies extension, continental break-up and seafloor spreading. Continental break-up models by Sleep (1971) show that the lithosphere is heated during rifting and uplifted over a broad region. The lithosphere is restored to its original state by cooling as it moves away from the mid-ocean ridge, but in the meantime mechanical extension and erosion will have thinned the crust. The net result is a sediment-filled depression at the margin caused by subsidence. Continental margin sedimentation processes and their interactions have a major impact on the shapes of the slopes and are strongly influenced by prevailing climatic and oceanographic conditions (Mutti and Normark, 1991; Stow et al., 1985). This makes the study of extended continental margins -hereon referred to as passive margin- important to palaeo-oceanographic and palaeo-climatic archives, hydrocarbon

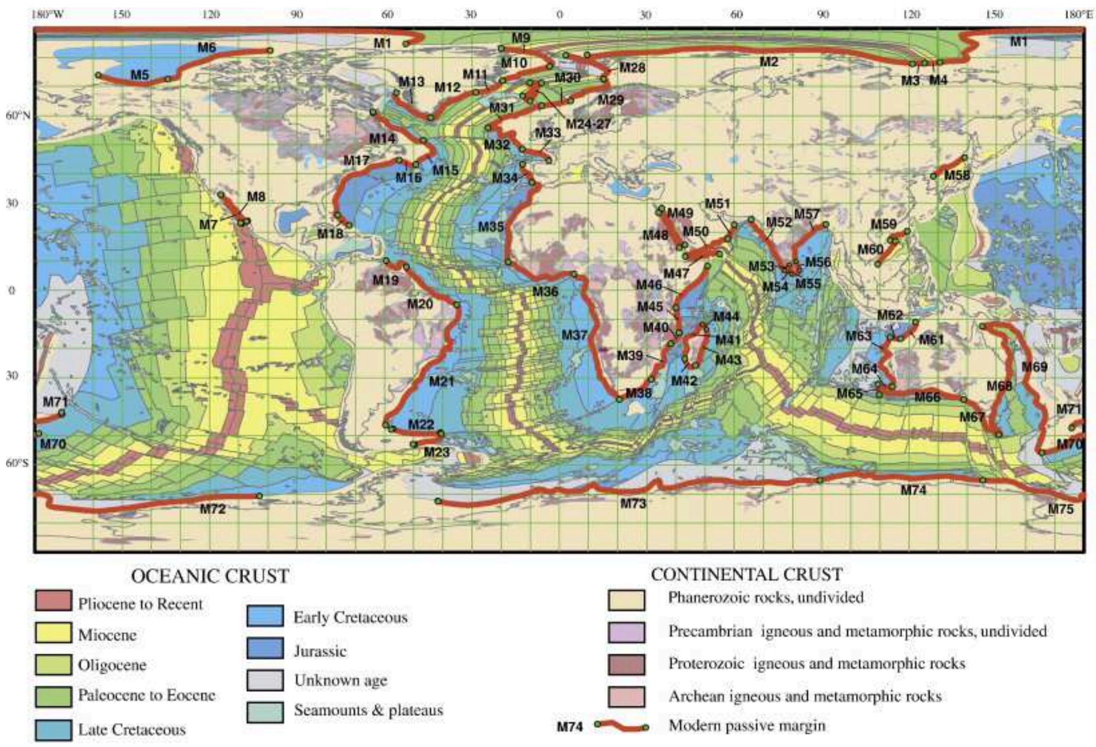


Figure 1.1:Global distribution of extended passive continental margins. (Bradley 2008); with permission from Elsevier.

reservoirs and determining instabilities and geohazards.

Most passive margins are comprised of typical features. The upper part of the transitional crust between the continental and oceanic crust is characterized by normal faults caused by a brittle response to extensional forces. These margins are overlain by thick sequences of sediments and are morphologically subdivided into the continental shelf, slope and rise (Figure 1.2). Terrigenous sediments are brought in from the continent over coastal plains and accumulate over the continental shelf in a deltaic environment. The sediments are transported further to the continental rise or into the abyssal plains by turbidity and longshore currents.

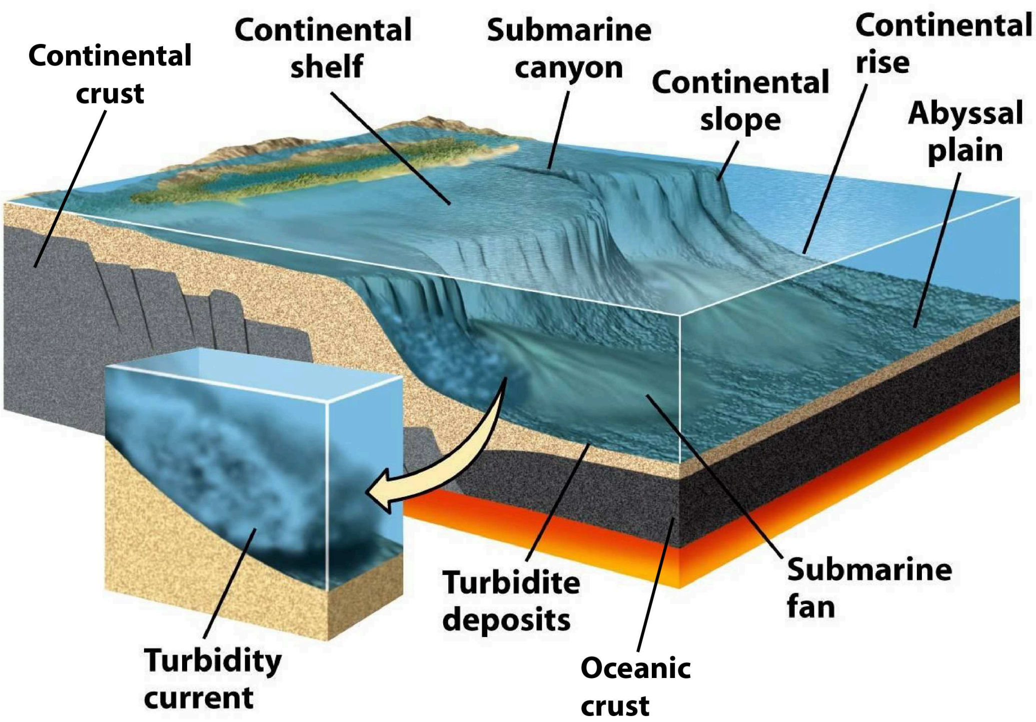


Figure 1.2: Sketch of a passive margin that acts as a transition from continental to oceanic crust overlain by thick sequence of sediments (modified from Grotzinger & Jordan, 2010).

1.2. From rift margin to passive margin

The separation of supercontinents to form oceanic basins and passive margins takes place in 3 stages: (a) Rifting, (b) Break-up and (c) Spreading (Figure 1.3)

Rifting

Before the start of separation begins, crustal thinning and warm mantle upwelling deform continental lithosphere. The rifting associated with crustal thinning creates a cluster of narrow valleys that are bounded by normal faults (e.g. Tanzania Rift Valley).

This can be accompanied by massive volcanism as in the case of Gondwana break-up during Early Jurassic times when Karoo and Ferrar basalts were emplaced in Africa and Antarctica respectively (Duncan et al., 1997; König and Jokat, 2006; Reeves and de Wit, 2000).

Break-up

The rifting culminates in the break-up and separation of the continent with a new spreading centre along a single valley where new oceanic crust is created along the ridge. The rest –the failed rifts- is preserved, as elongated valleys that come to be filled

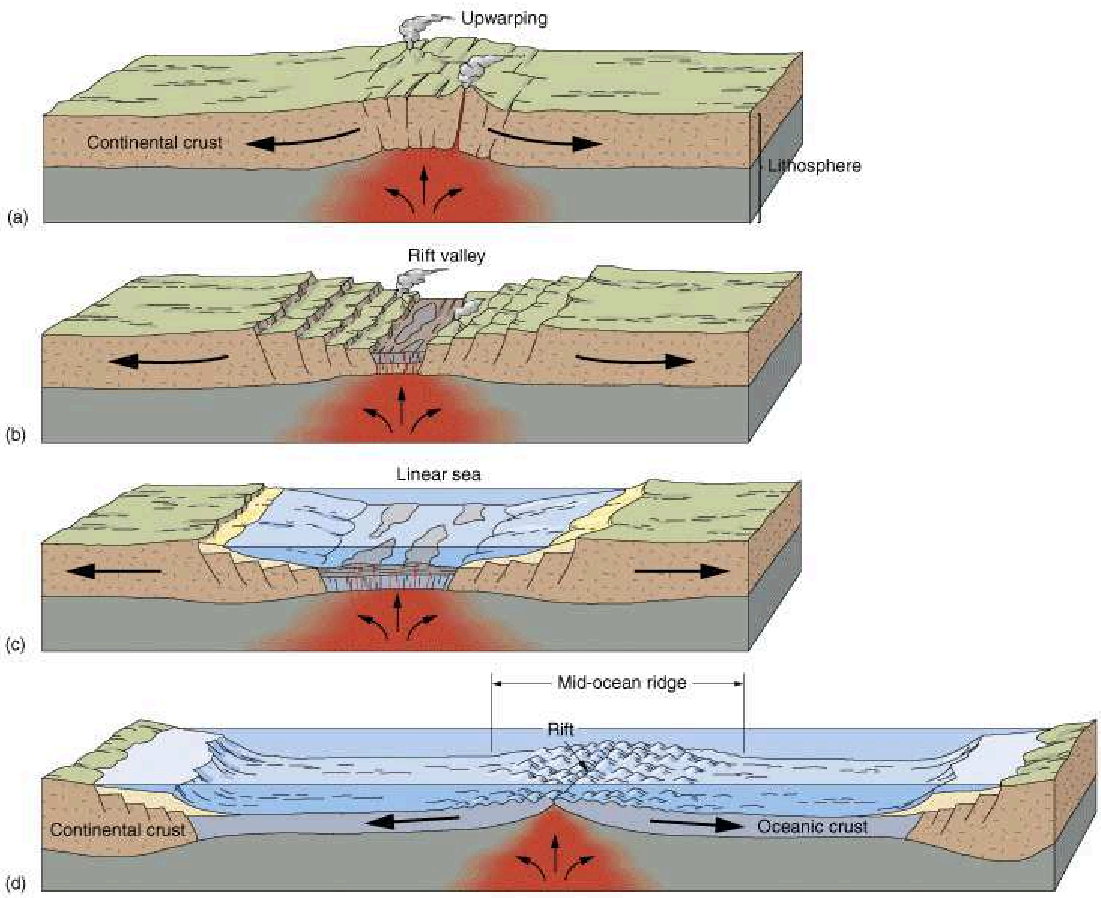


Figure 1.3: The process of continental break-up and seafloor spreading that eventually culminates with the formation passive margins (source: http://www.csus.edu/)

by continental sediments. Enclosed basins or lakes are formed in the depression and are filled with terrigenous sediments.

Seafloor Spreading

As the new oceanic crust is formed, the continents and older oceanic crust drift apart. The oceanic crust becomes dense as it cools downs and subsides at the continental margin. The subsequent basins may evolve in to large oceans with mid-ocean ridges in the middle. The passive margin is subsequently covered by sediment platforms of continental and marine origin.

1.3. How do environmental settings control turbidite systems and submarine fans at passive margins?

Rivers flow along rift grabens that erode the continent and deposit terrigenous sediments in river deltas. Turbidity currents determine how the sediments are deposited in the basin. Submarine fans are physiographic features consisting of sediment piles that are a deposited by turbidity currents seaward of large river mouths and submarine canyons (Figure 1.4). The development of submarine fans is primarily controlled by their tectonic setting and activity, sediment type and supply, and additionally by sea-level variations

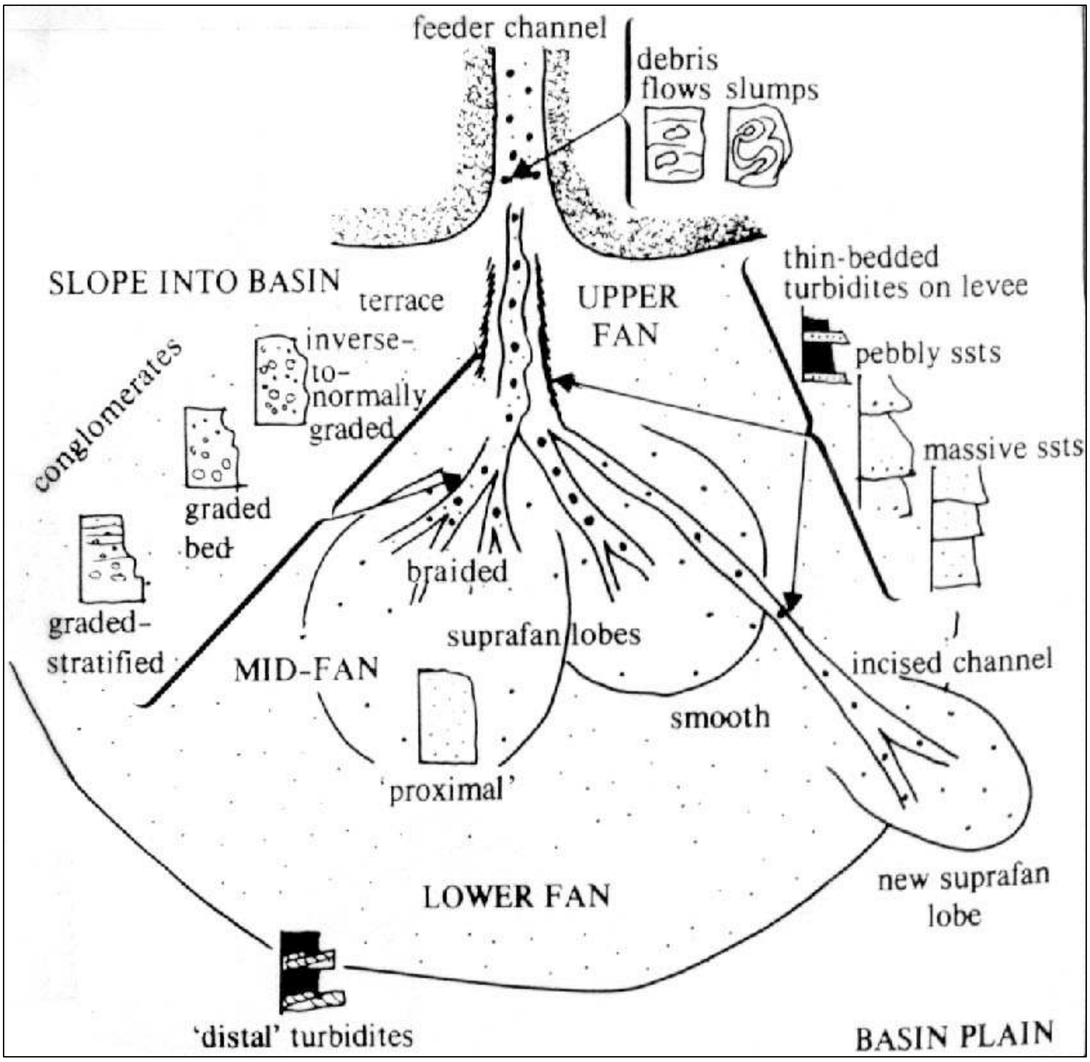


Figure 1.4: Schematic sketch of submarine fans showing different parts of the fan and their characteristic stratigraphies (Walker & Mutti, 1973)

(Stow et al., 1985). Secondary controlling mechanisms include climate and vegetation, original source-rock composition, relief and tectonic activity in the hinterland and local marine conditions including but not limited to bottom current, temperature, water depth, and biogenic environment (Stow et al., 1985).

Tectonic settings exert a first-order control on the types of fans developed by affecting rates of uplift and denudation, drainage patterns on coastal plain, shelf width, continental margin gradients, gross sediment budget, the morphology of the basin, and local sea-level changes (Nelson and Kulm, 1973). Although the tectonic setting within the Mozambique Basin is still unknown, but onshore evidence for several episodes of uplift of varying magnitude of the African Continent have be identified since the Cretaceous (Burke, 1996; Partridge and Maud, 1987). This makes Mozambique an ideal location to study the influences of onshore tectonics on turbidite systems and submarine fans.

Sea-level variations have a profound effect on the near shore realm as well as on patterns of deep-sea deposition and resedimentation. Deposition and erosion are strongly controlled by *accommodation space* i.e., area available for sediment deposition. One of the factors that determine *accommodation space* is local sea-level variation. Sea-level high stands coincide with relatively inactive phases in many fans (Stow et al., 1985). During such times, sediment is trapped in estuaries, lagoons or other such nearshore environments. Submarine fans may still be active due to bottom currents and other turbidity currents, but at significantly reduced rates (Stow et al., 1985). On the other hand, sea–level lowstands result in the development of narrow shelves with more sedimentation as well as funnelling of sediments through canyons and valleys to deeper basins. Fluctuation in sea-level variations can result in different styles of fan growth.; progradtional clinoforms, rejuvenation and channel incision during sea-level, and regradational sequences and channel abandonment during sea-level rise.

Sediment type and supply

Two end-member types of fan and a third non-fan system could result from variations in sediment type and the nature and rate of sediment supply (Stow et al., 1985). The elongated fan develops in response to a medium to high input of sediments of mixed grain size with mud and very fine sand as the dominant composition. These types of fans generally have a single major primary source and one active channel at a time and one or more feeder channels across the slope. The radial fan results from smaller sediment input with sand grade more abundant than mud. The slope apron system is a closely related turbidite system characterized by a low to medium rate of supply of mixed sediments. Most modern-day fans can be classified as one of these end members or hybrids thereof (Figure 1.5).

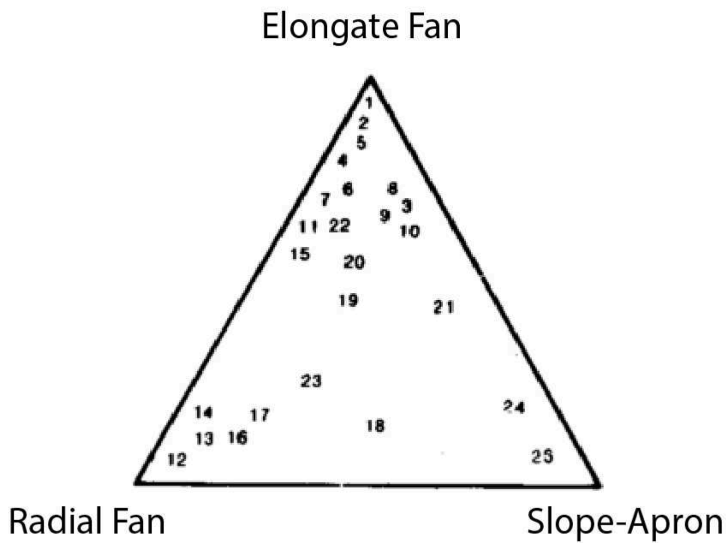


Figure 1.5: Ternary classification of submarine fans with positions of modern fans with respect to the three end member modes: elongate fan, radial fan and slope-apron systems (Stow et al., 1985); with permission from Springer.

1. Bengal
2. Indus
3. Mississippi
4. Zaire
5. Amazon
6. Reserve
7. Rhone
8. Laurentian
9. Monterey
10. Delgada
11. Astoria
12. La Jolla
13. Redondo
14. Navy
15. Nitinat
16. Coronado
17. San Lucar
18. Ebro
19. Hudson
20. Orangedo
21. Crati Lucas
22. Nile (Rosetta)
23. Menorca
24. Normal slopes and rises
25. California Continental Borderland basin slopes

1.4. Marine sediments as archives for palaeo-environmental conditions

Studies of palaeo-environments are based on analyses of marine sediment compositions along continental margins to establish, among many parameters, their mineral composition, grain size, microfossil fauna and flora, and isotopic composition. These marine archives provide important information on climatic conditions and environment at the time of burial. These methods provide information on the evolutionary history at a given location. This can be extended to a regional scale when location information is used in conjunction with other methods like the analysis of small and large-scale submarine structures that are deposited by different processes. As described above, these structures are products of onshore topography and paleoclimatic conditions. Over the last decades, several survey methods have been developed to map subsurface features from the seafloor downwards until several kilometers. These methods include bathymetry sounding and parasound, sidescan sonar, reflection seismics, wide-angle refraction, magnetics, and gravimetry.

1.5. Palaeobathymetry modelling

Passive margins are characterised by large sediment thicknesses of up to 12 km (Watts and Ryan, 1976). The sediment thickness off Mozambique ranges from 7 to 12 km and obscures the basement, complicating the task of understanding the margin's structural evolution. However, the development of techniques such as backstripping (Watts and Ryan, 1976) have enabled the subsidence and uplift history to be determined using stratigraphic data. The main result of backstripping has been to show that the accumulation of sediments at passive margins is the result of two main factors: cooling following heating of the lithosphere at the time of rifting and loading due to the sediment accumulation. Other factors (e.g. sea-level, compaction, salt tectonics, magmatism) contribute, but it is generally agreed that these are of secondary importance.

1.6. Why is the Mozambique Basin important?

The sedimentary basin off Mozambique is the second largest basin along the East African Margin, after the Somali Basin of approximately same age (ca. 165 Ma). Despite its economic potential and importance in Gondwana break-up, it continues to be poorly surveyed. Very few studies have been published in the last decades that focus primarily on the hydrocarbon potential using vintage seismic data (De Buyl and Flores, 1986; Droz and Mougenot, 1987a; Kolla et al., 1980; Nairn et al., 1991; Salman and Abdula, 1995). Several models exist to constrain the initial break-up along the East African Margin but not all inconsistencies concerning overlap or separation are resolved (König and Jokat, 2006; Leinweber and Jokat, 2012; Mahanjane, 2012; Reeves and de Wit, 2000; Reeves et al., 2002). Some recent studies focus on the crustal structure and evolution of the Mozambique Basin using new geophysical data acquired in the last decade (König and Jokat, 2010; Leinweber et al., 2013; Mahanjane, 2012; Mueller et al., 2016). They have already improved our understanding of the break-up and evolution of the region if not challenging previous interpretations.

1.7. Open questions and objectives

As illustrated in the previous section, a wide knowledge gap exists concerning the break-up of Gondwana and the evolution of sediment depositional architecture in the Mozambique Basin. The MoBaMaSis project was established in 2007 with collaboration between German (BGR and AWI) and French (IFREMER and IPEV) research institutes and to investigate the Mozambique Basin in terms of its structure and formation history with emphasis on its hydrocarbon potential and in a larger framework, to examine its role in the opening of Southern Ocean and break-up of Gondwana.

Within the scope of this project, several geophysical datasets were acquired during the expedition MD163 onboard the French research vessel Marion Dufresne. The objective of the project was focused to address several key questions:

1. When did seafloor spreading in the basin start?
2. What are the constraints on continental break-up and subsequent seafloor spreading?
3. What is the crustal structure of the Mozambique Basin?
4. How did the basin evolve from a rift basin to a passive margin basin?
5. What is the contribution of the Zambezi River to sediment accumulation in the basin?
6. What are the controls on the depositional architecture?
7. Has the basin been affected by tectonic activity since its formation?

Volker Leinweber, in his thesis (2007-11), used the dataset to investigate the first 3 questions on crustal structure and break-up. This dissertation is a continuation of the project under the supervision of Prof. Dr. Wilfried Jokat with support from AWI to investigate the other issues not addressed so far. The main focus of my research is to identify the relationship between sediment supply and transport to the basin and onshore activity. To address this objective, the regional stratigraphy has to be extended from the shelf into the basin. This makes it possible to set a time constraint to sediment features contained within each stratigraphic unit.

1.8. Scientific contribution

The objectives outlined in the previous section are addressed in Chapters 4-6. These are individual contributions in the form of manuscript that have been prepared for publication in ISI-peer reviewed journals. This section briefly summarizes the approach used in each study and the outcome of the results. The contribution of each of the authors has been specified below.

Chapter 4 describes the results from the interpretation of seismic profiles in the first manuscript that were acquired during the MoBaMaSis project. The evolution of the Mozambique basin during Mesozoic times is described. It provides the general stratigraphic framework that has been extended from studies in adjacent region. This stratigraphy forms the basis for the subsequent palaeobathymetric modelling study. J. A. Castelino contributed to all the work that includes reprocessing and interpreting all the seismic data, making bathymetry maps, compiling stratigraphic table and writing the manuscript. W. Jokat and F. Klingelhoefer provided additional suggestions and comments. C. Reichert and D. Aslanian are the co-proponents of the MoBaMasis project. All, except J. A. Castelino, were a part of the scientific party on the expedition MD163 that contributed to the preliminary interpretation onboard. The manuscript has been published in Journal of Marine and Petroleum Geology.

Chapter 5 shows the results of palaeobathymetry modelling of the Africa Antarctic corridor between the Mozambique and Riiser Larsen Sea conjugate margins. J. A. Castelino collected all the lithostratigraphy and modified the age grid for palaeobathymetry models and manuscript writing. G. Eagles provided the plate rotation parameters and wrote parts of the manuscript relating to the discussion of anomalous bathymetry. W. Jokat provided additional comments and suggestions. The seismic data in the Riiser Larsen Sea was made available by PMGE (Russia) through the Antarctic Seismic Data Library (SDLS) under the auspices of the Scientific Committee on Antarctic Research (SCAR) and the Antarctic Treaty (ATCM XVI-12). They have been duly acknowledged in the publication. The manuscript has been submitted to Earth and Planetary Science Letters and is currently under review.

Chapter 6 describes the development of the Mozambique Fan since the Late Cretaceous. The origin of trigger mechanism for fan development and the controlling factors on fan morphology are discussed. J. A. Castelino prepared all the figures and schematic sketch of the turbidite system. W. Jokat provided suggestions for improving the manuscript. The manuscript is currently in preparation for Marine Geology with J. A. Castelino. C. Reichert is the co-proponent of the MoBaMaSis project and chief scientist of the expedition MD-163

Chapter 2: Geological background and regional setting

2.1. Physiographic setting

The Mozambique Basin, located in southwest Indian Ocean, is an almost triangular trough bounded by the Mozambican coastline along the northwest and west and by the Madagascar coastline and the submarine Davie Ridge lineament to the east (Figure 2.1). The Davie ridge is a relict of the dextral strike-slip movement that guided Madagascar from break-up in the Somali basin to its present location until Aptian (Bassias, 1992). The Mozambique passive margin is a product of continental break-up of Gondwana and subsequent deposition of a thick sedimentary sequence on the shelf area with the Zambezi River as the primary input source.

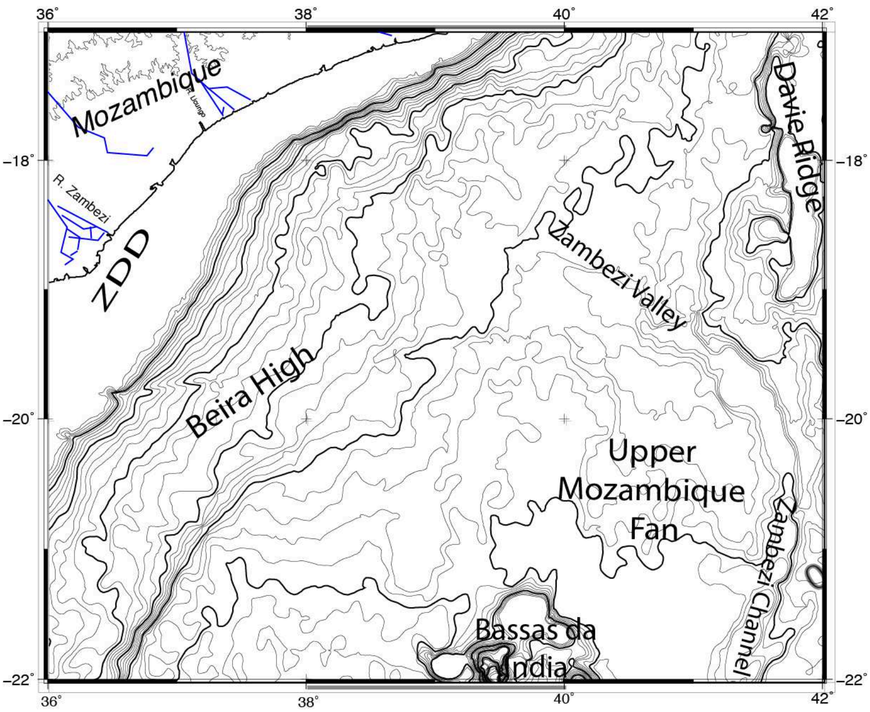


Figure 2.1: Physiographic map of the Mozambique Basin showing major features. A wide shelf off the Zambezi River mouth is located in the Zambezi Delta Depression (ZDD)

2.2. Structural framework

The extended continental margin off Mozambique originates from the break-up of Gondwana in Middle Jurassic (Rabinowitz et al., 1983). The rifting in Mozambique during the break-up of Gondwana was accompanied by massive volcanism. In Africa, the volcanism formed the continental Karoo flood basalts and the Ferrar flood basalts in Antarctica (Figure 2.2). The timing of break-up and the early kinematics that separated the block have been much discussed. Although it was previously thought that Madagascar was juxtaposed to Mozambique(Foerster, 1975; Kamen-Kaye, 1982), it is now established beyond doubt that the latter drifted to its current position from the Somali Basin (Cox, 1992; Eagles and König, 2008; König and Jokat, 2010; Leinweber and Jokat, 2012; Reeves and de Wit, 2000; Reeves et al., 2002). These studies propose a two-phase process for the separation of east and west Gondwana. Beginning with a anti-clockwise rotation for Antarctica (East Gondwana block) with respect to Africa and then drifting southwards. The change in spreading direction is very well observed along magnetic lineations and fracture zones along the African-Antarctic Corridor in the Mozambique Channel (Eagles and König, 2008; Leinweber and Jokat, 2012)

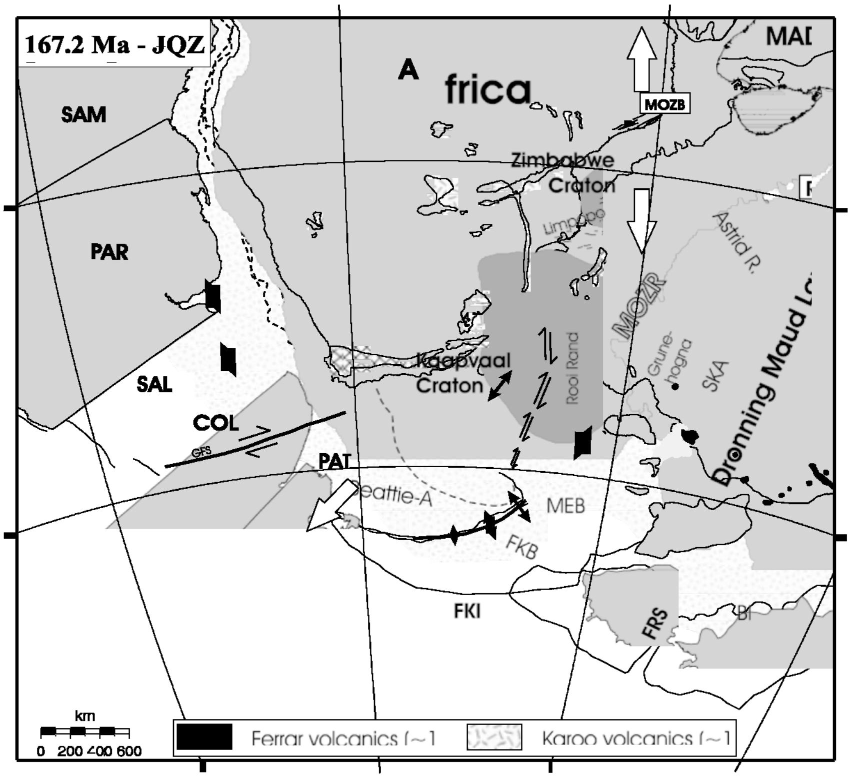


Figure 2.2: Reconstruction of the break-up of Gondwana after the initial east-west oriented rifting between Africa and Antarctica that was preceded by emplacement of Karoo and Ferrar volcanics by excessive volcanism (modified König & Jokat,2006)). AFFZ, Agulhas Falkland Fracture Zone; AFR, Africa; ANP, Antarctic Peninsula; Beattie-A, Beattie Anomaly; C.A., central anomalies [Ferris et al. , 2000]; COL, Colorado; E, East Antarctica; EWM, Ellsworth Whitmore mountains; FKB, Falkland Plateau Basin; FKI, Falkland Islands; FRS, Filchner-Ronne Shelf; GFS, Gastre Fault System; IND, India; LZS, Lazarev Sea; MAD, Madagascar;; MEB, Maurice Ewing Bank; MOZR, Mozambique Ridge; O-A, Orion Anomaly; PAR, Parana´; PAT, Patagonia; RLS, Riiser-Larsen Sea; RV, Rocas Verdes; SAL, Salado; SAM, South America; with permission from Wiley.

2.3. Regional Geology and stratigraphy:

Significant hydrocarbon discoveries off Mozambique have made it a frontier province for exploration. This has resulted in a very reliable stratigraphy in the Rovuma Basin in the north and Zambezi delta depression (Figure 2.3) and Limpopo delta in the south to identify source rock potential. Pioneering work by De Buyl and Flores (1986) in the 80s and later by Nairn et al. (1991) and Salman and Abdula, (1995) has laid the foundation for several studies thereafter. In order to answer one of the key objectives of the study, we extend this regional stratigraphy to the deeper abyssal plains of the Central Mozambique Basin where little is known. The basin evolution and history off Mozambique can be characterized by two contrasting regimes: (1) Rifting phase and (2) Passive margin phase.

This section gives an overview of the stratigraphy of the region that has been interpreted by De Buyl and Flores (1986) from several on and off shore wells around the Mozambique Plains.

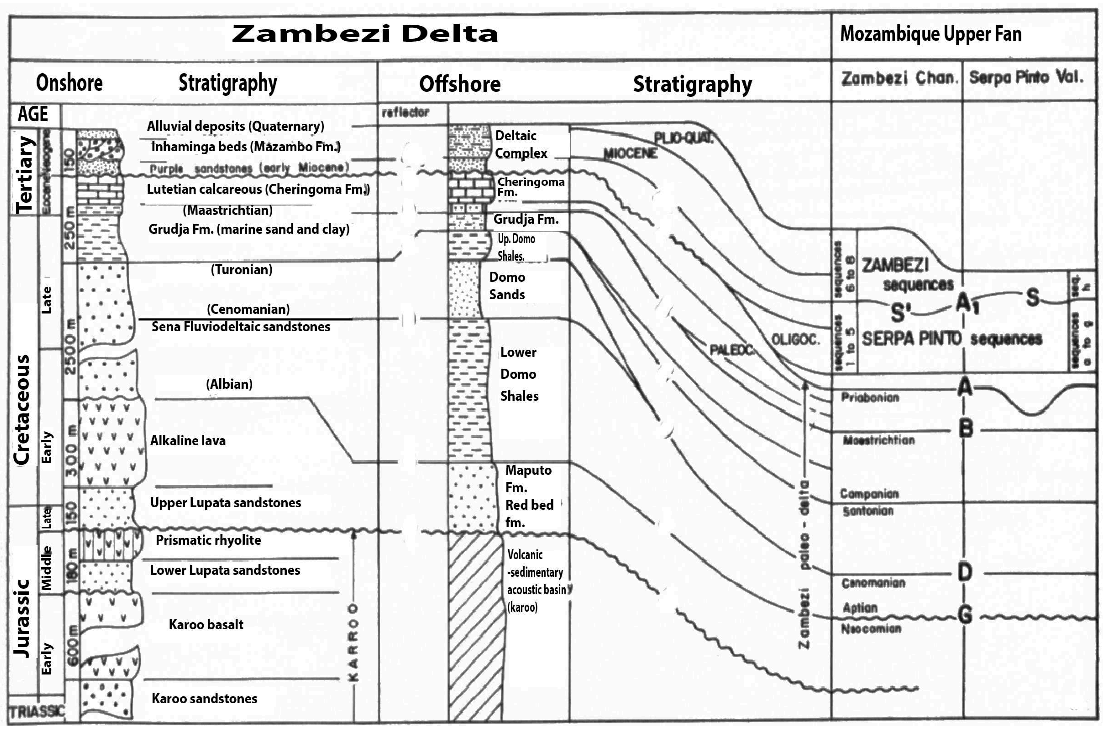


Figure 2.3: Stratigraphy of Zambezi Delta in the Mozambique Basin (modified from Droz & Mougenot, 1987)

Basement: The basement onshore is postulated to be of continental origin belong to the Karoo Supergroup. It is represented by the Stromberg series, which comprises of volcanoclastics, lava flows and sandstone and, the Ecca series associated with coal measures, shale and sandstone.

Upper Jurassic – Lower Cretaceous: Post-Karoo sediments of this strata consists of red continental sediments known as the “Red Beds” Formation.

Lower Cretaceous to Cenomanian: The sedimentary deposits of this age are a mixture of marine, continental and transitional facies. Marine sediments of Neocomian age assigned to the Maputo Formation comprises of glauconitic-quartzose sand- stones and arenaceous limestone, interbedded with argillites. The Sena formation forms a continental rock sequence of arkose sandstones, conglomerates and argillites enriched with coaly detritus. The Lower Domo shales forms the top of this layer that are deposited in a pelagic euxinic condition with up to 1% carbon of humic origin. The sequence does not strictly represent a chronostratigraphic but a change in facies.

Cenomanian – Maastrichtian: The Domo formation continues in to the Upper Cretaceous sequence with the Domo sands separating the Upper and Lower domo Shale formation. The Lower Grudja formation completes this sequence.

Paleocene- Oligocene: Cenozoic sediments represent passive continental facies built by turbidity currents and submarine fans. The upper Grudja composes of glauconitic sand, clay and marl with bands of limestone. The Cheringoma Formations occurs as numulitic limestone with bands of clay and calcareous sandstone. Onshore the presence of reef massifs and chains indicate the location of the proto-shelf to be much further landwards.

Oligocene – Neogene: Post Oligocene sediments are mainly deltaic sediments of Jofane sequence with sandy limestone and dolomites. Coral debris and oolites are a common occurrence in the Jofane Formation and indicate a high energy environment.

Quaternary deposits occur as continental deposits of ancient dunes, river terraces and lake that are widely distributed on the shelf with the maximum thickness in the Zambezi Delta.

Chapter 3: Methods

The data off Mozambique used in the study were mainly collected during R/V Marion Dufresne Expedition MD163 in 2007. The expedition was a joint collaboration between German and French institutes (BGR, AWI, IFREMER and IPEV) to investigate the structure and formation history of the Mozambique Basin. Several geophysical datasets were collected that include reflection and wide-angle seismic data, as well as gravity, magnetic and bathymetric data. Only the acquisition and processing of the reflection seismic and bathymetric data used in this study has been described in detail in the following sections. 9 MCS profiles with a total length of ~2250 km of seismic data were processed and analyzed in this study.

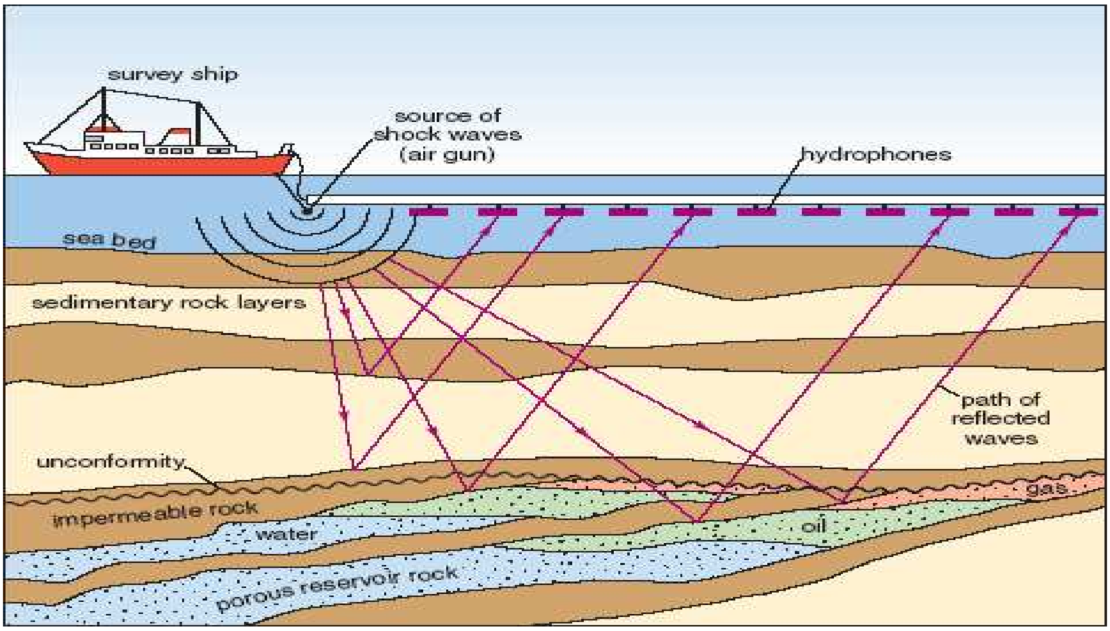


Figure 3.1: Illustration of 2D marine seismic data acquisition similar to the one used in the MoBaMaSiS project with an airgun cluster and 3000 m streamer cable. (Modified from http://openlearn.open.ac.uk/mod/resource/view.php?id=172129)

The interpretation of our first and third manuscripts is mostly based on the results and analysis of the seismic profiles acquired during the MoBaMaSis project and processed by me.

The seismic data in the Riiser-Larsen Sea used in chapter 5 were collected and processed by PMGE (Russia). They are available from the Antarctic Seismic Data Library (SDLS) under the auspices of the Scientific Committee on Antarctic Research (SCAR) and the Antarctic Treaty (ATCM XVI-12).

3.1. Multi-channel seismic data acquisition:

Profiles BGR07-20070201 and BGR07-20070202 (hereby refraction profiles) were acquired simultaneously with wide-angle data and therefore have a different set up in comparison to the remaining seven profiles (hereby reflection profiles). The data acquisition follows a standard operating geometry with a cluster of airguns towed behind the ship for the seismic source followed by a long streamer for recording the reflected seismic signals (Figure 3.1).

3.1.1. Airgun system

The AWI G-Gun airgun cage with an array of 6 guns, each of 520 cu.in with working pressure of 145 bar and towing depth of 8 m was used as a seismic source during the acquisition. Triggering and synchronisation was controlled by a SYNTRON GSC-90 system. For reflection profiles, 5 of the guns with a total volume of 42.6 l were operated with a shot interval of 18 seconds, thus providing a shot interval distance of 50 m at a speed of 5.4 knots. Additional two guns were used (total volume 67.2 l) were used for the refraction profiles with a short interval of 60 seconds.

3.1.2. Seismic data acquisition

BGR’s SEAL system and 3000 m long digital cable with a lead in of 190 m were used for recording the seismic data. The streamer consists of 20 seismic sections (ALS) with 240 channels in total (12.5 m spacing). Each channel records with a group of 16 hydrophones The recording length was set to 14 seconds with 2 ms sampling interval.

3.2. Seismic Data processing

The aim of seismic data processing is to provide reliable images of the subsurface and geological features by using mathematical principles to supress background noise and, amplify coherent signals. Broadly, seismic processing can be classified in 3-steps, namely pre-processing, pre-stack processing and post-stack processing. Figure 3.2 illustrates the general work flow for seismic data processing.

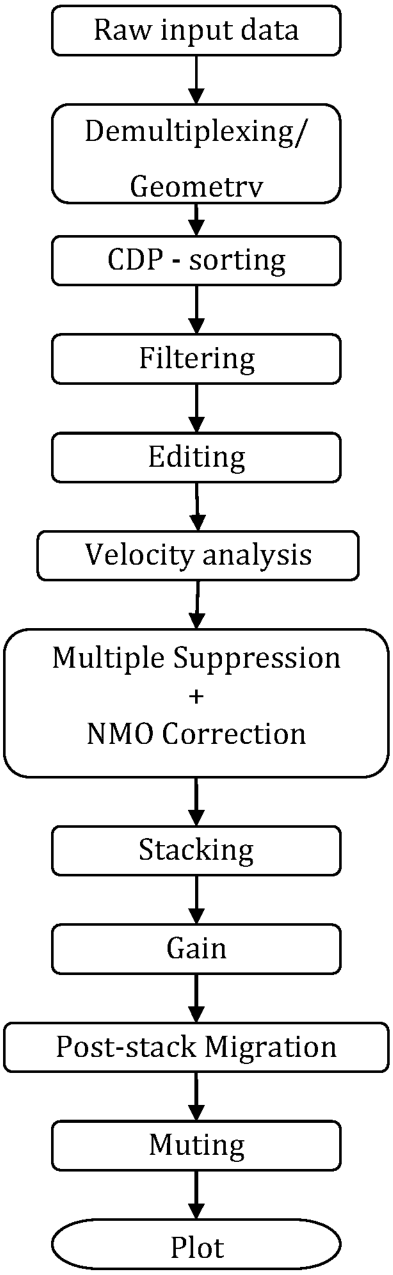


Figure 3.2: Workflow of seismic data processing

3.2.1. Demultiplexing and geometry

Demultiplexing is the first step in pre-processing where time sequential data is sort in to trace sequential order for each shot. The navigation data from the GPS antenna is imported into the rectangular co-ordinate system. During the subsequent process, geometry set up information is stored in the header data by linking the geographic data from the GPS file such as longitude, latitude, water depth and time to each shot by using time as a common denominator. The traces are required to be grouped into similar entities for further processing. They can be ordered by Channel, Shot or CDP (Common Depth Point). Most seismic routines require the traces to be ordered by CDP especially for velocity analysis. All the rays reflecting from a common depth point are grouped together (CDP gather). The CDP interval was set to 50 m for the refraction profiles and 12.5 m for the reflection lines in order to achieve sufficient fold and highest resolution.

3.2.2. Filtering

Seismic signals contains a broad range of frequency some of which that does not originate from the source and results in a ringing effect. During the process of filtering, unwanted signal frequencies that are recorded with the reflection events can be removed by allowing only a band of usable frequencies to pass. Frequency analysis of the signal shows that most of the energy lies between 10 and 60 Hz with a peak in the range of 20-60 Hz. The process of filtering already gives a more clear picture by removing high frequency noise. An Ornsby bandpass filter for 10-80 Hz with 5 Hz ramp on either side is used in most cases during the routine.

3.2.3. Velocity analysis and NMO-correction

The subsurface velocity modelling is extremely important as it plays a vital role in several seismic processing routines like multiple suppression, migration and stacking. The arrival time of reflections from a single event from the subsurface depends on the travel path of the signals. For a reflection from a point located in the subsurface with a constant velocity, the time difference between a given offset and zero offset is called normal moveout (NMO) and can be calculated as

$$\Delta t = t(0) - t(x) = \frac{x^2}{v^2 t_0}$$

where v = *velocity through the layer*
t_0 = *total travel time for a round trip at zero offset*
x = *offset distance of receiver from source*

For a wave travelling through multiple layers with different velocity, the root mean square (rms) is computed as

$$v_{rms} = \sqrt{\frac{v_1^2 t_1 + v_2^2 t_2 + \ldots}{t_1 + t_2 + \ldots}}$$

However, we make a simple assumption that the reflecting horizons are horizontal, i.e., the angle of incidence and reflection to the vertical are similar. This assumption would not work in case of strong dipping units and, hence, the method is not very optimal.

In Focus™, velocity analysis is performed using VELDEF module. It provides an interactive option to select best fitting hyperbola defined by RMS velocity. Picking of velocity is assisted by a semblance of coherent trace energy (Figure 3.3).

Velocity analysis is done every 50 - 100 CDPs depending on topographic variations along the profile. The process was repeated in an iterative method where deeper reflectors could be identified after subsequent multiple suppression filters.

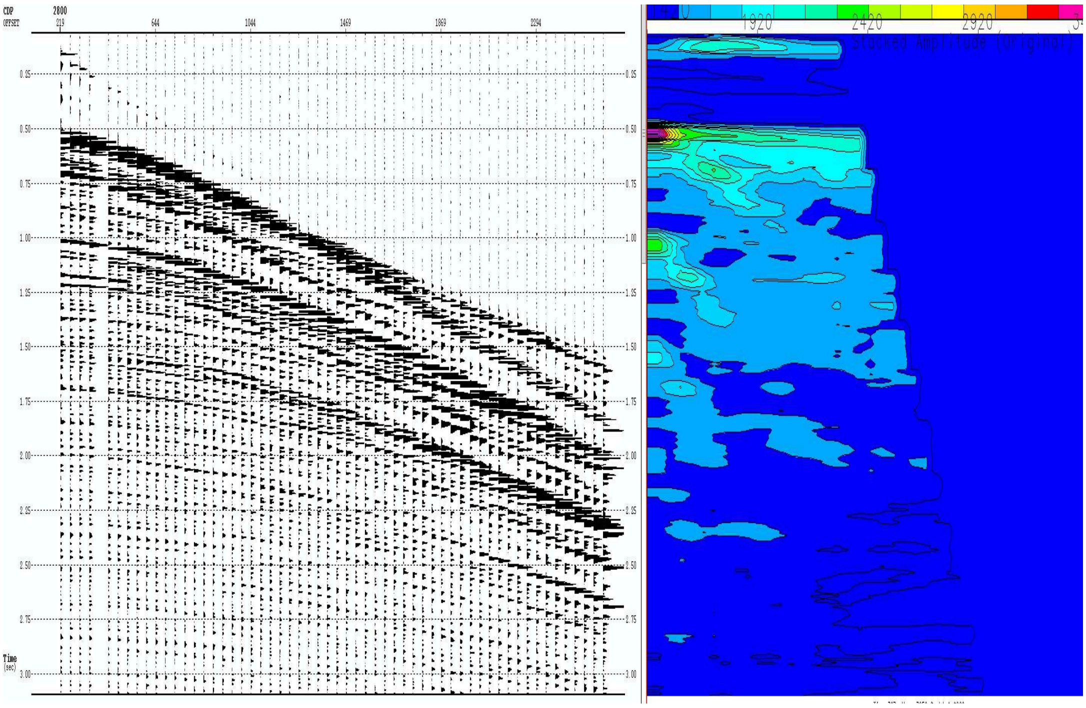


Figure 3.3: RMS velocity picking in Focus™ with applied Ornsby filter 10 – 60 Hz. Semblance window of magnitude of stacked traces against RMS velocity

3.2.4. Multiple Suppression

F-K Domain Filtering

F-K transformation plots dipping reflectors to points in the F-K domain using a double Fourier transform. Signals from a seismic reflector in a CDP gather that do not have a dip plot on the vertical axis, whereas upward dipping and downward dipping reflectors map on to negative and positive quadrant respectively. An NMO-corrected gather with velocity model that is in between primary and multiple velocity results in primary signals mapping to negative quadrant and multiple signals to positive quadrant.

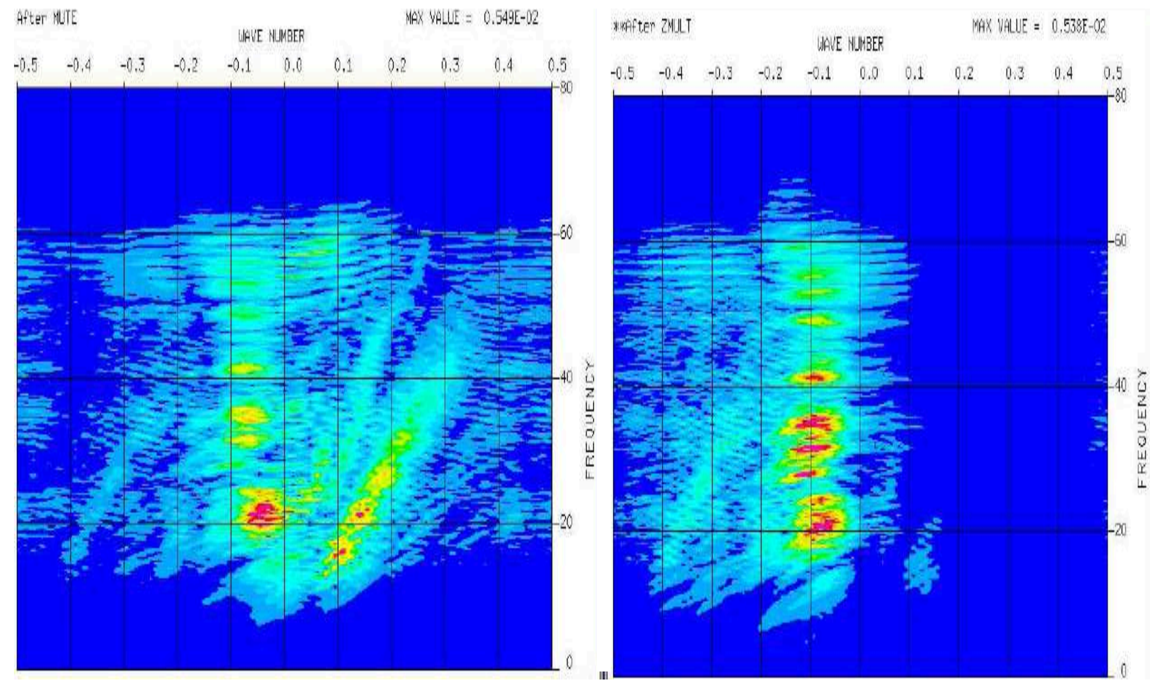


Figure 3.4: Transformation of over corrected CDP gather between 1.0 and 2.0 s into F-K domain. 3 distinct zones can be identified that are located between -0.1 and 0.2 . After Filtering, all the energy in the positive quadrant is suppressed

In Focus™, the module ZMULT performs the F-K transformation of the data and suppresses undercorrected reflectors (Figure 3.4). Before seismic data are filtered using ZMULT it must be prepared such that the primaries are overcorrected and the multiples are undercorrected. An over-correction parameter (OVC) can be applied to the subsurface velocity model and is calculated from the mean move-out time for primaries (t_p) and multiples (t_m) (source: Focus™ manual).

$$OVC = (t_m - t_p)/2$$

$$t_{(p,m)} = t_0 + X/V_{(p,m)}$$

where, *t_0 = two way travel time*
X = reference offset
$V_{(p,m)}$ = veloctiy of primaries and multiple

NMO corrected CDP is followed by a time variant OVC that is calculated using the above relation is well separated in F-K domain. The suppressed amplitude in the positive domain results in reduced multiples in the X-T domain (Figure 3.5).

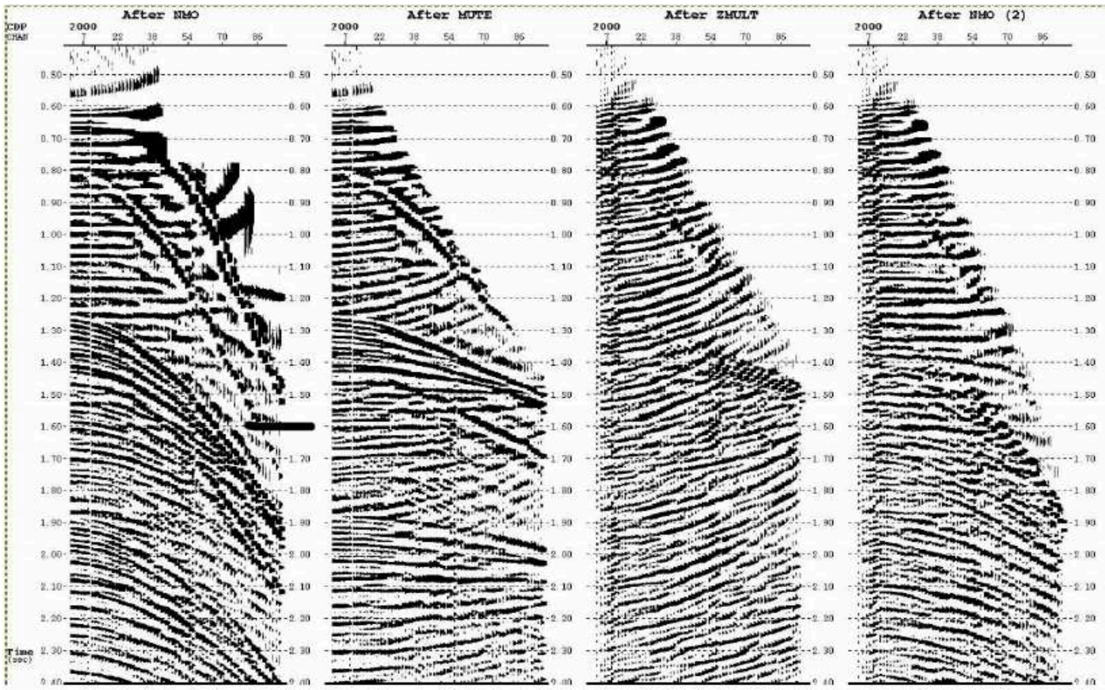


Figure 3.5: Steps for multiple suppression with F-K filtering. After ZMULT, multiples in the far offset align with the primaries that influence the final stack

B. Wavefield Extrapolation method (SRMA)

SRMA is a wavefield extrapolation method where the multiples are estimated by extrapolating primary waves such that they act as a source. Extrapolation is achieved by convolving two traces from different shots, hence, it requires that traces are shot ordered. Multiple suppression is done in 3 steps:

Zero-offset Interpolation

In order to compute the first order multiple for a specific offset distance, traces from half the offset distance are required and every one third of the distance of the offset for second order multiple. In practice, it is not possible to have a zero-offset and the nearest offset is at a considerable distance away. In current dataset, it is 190 m, which implies 16 missing traces for the reflection profiles . In such a case, multiples for traces up to 400 m cannot be reconstructed for the first order, 600 m for the second order and so on. Therefore, traces for the near offset has to be interpolated. This process regularizes traces and also accounts for traces that are required for extrapolating recorded multiples but lie in between two recorded traces. The module does not use a seafloor topography model but extrapolates from the first recorded sample, therefore, it requires that the gather be precisely muted until the seafloor to remove water column noise and other interferences.

Multiple prediction

In the second step, a Taylor series is generated that predicts multiples by method of extrapolation and phase reversal for multiples (Focus^{TM} Help documents). Seismic traces convolve with itself along the surface. (Figure 3.6)

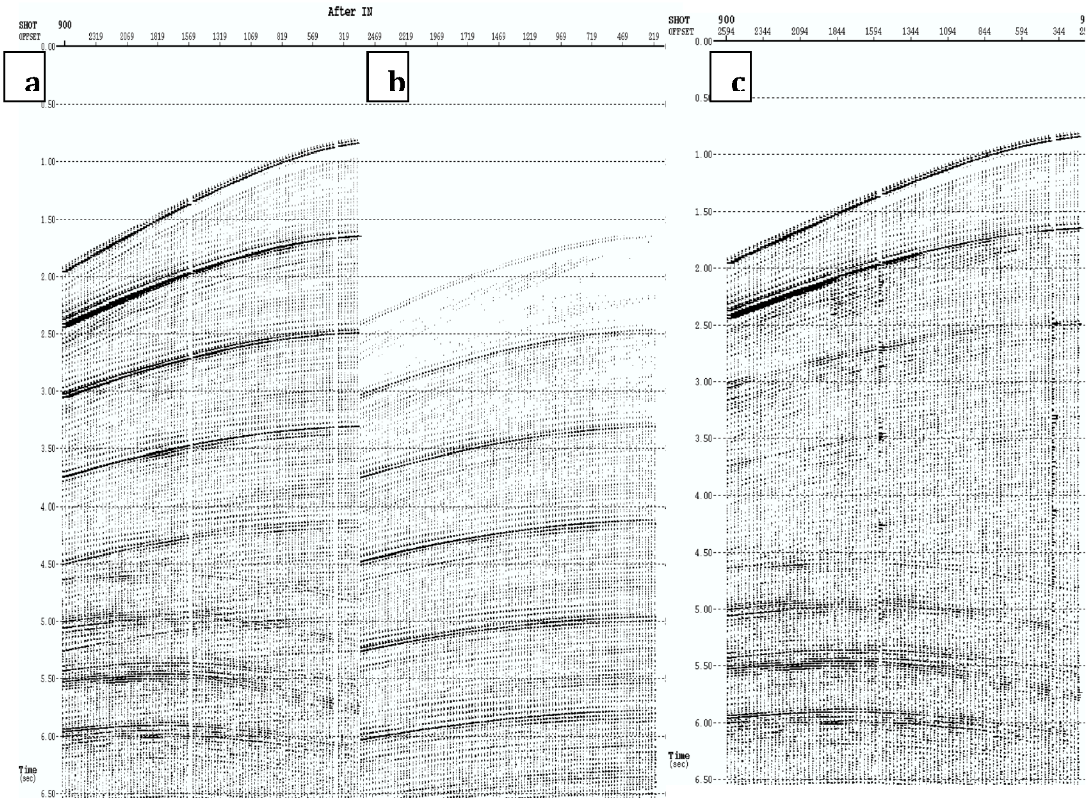


Figure 3.6: Multiple suppression with SRME (shot gather). a) Interpolated shots (only the traces from the input shot gathered are displayed). b) Extrapolated first order multiples, note the good correlation of extrapolated multiples to the input multiples c) Shot gather after adaptive subtraction of the traces.

Multiple subtraction

In the last phase, the predicted multiples are correlated to the original trace, scaled in amplitude and subtracted from the original trace. In Focus^{TM}, the above steps are achieved by two modules. The SMACTRM module interpolates traces to zero-offset and generates n terms of the Taylor series. For computational reasons it is important to define shot intervals and receiver intervals such that every station has a shot and receiver. Missing receiver traces are interpolated using a velocity function defined by HANDVEL. Missing shots are determined using RATIO which copies nearest shot for missing stations. In order to be time efficient, only up to second order multiples are predicted to target only until depths where multiples are strong. SMACMS module uses the Taylor terms stored in header files to subtract the predicted signals from the original shot gather. (Figure 3.6)

3.2.5. Stacking

Stacking process sums all the traces along a horizontal line to produce a single representative trace of a given CDP. A NMO corrected data with stretched trace muted is used as an input. The seismic data were stacked using alpha-trim median stacking algorithm where the lowest 15% and the highest 15% amplitudes are excluded in the summation of the traces.

3.2.6. Migration

Migration of seismic data moves dipping events to their correct positions, collapses diffractions, increases spatial resolution and is probably the most important of all processing stages. The MIGFX operation is based on a finite-difference approximation to the monochromatic wave equation. It can handle velocity variations in both the lateral and vertical directions. Finite Difference (FD) Time Migration uses a constant velocity model of 1500 m/s and leads to the collapse of diffraction hyperbolas and bowties as well as the proper imaging of tilted reflectors. The FD Migration is less susceptible to deviations from the velocity model than other migration algorithms, it is thus especially suited to the data in this study due to the assumed constant velocity model and rapidly changing geology throughout seismic profiles. The complex geology and seafloor topography in the study areas required a successful migration in order to allow meaningful interpretation to be carried out.

3.3. Bathymetry

Multibeam bathymetric data on MD163 was recorded with a hull mounted multibeam echo sounder (MBES) Seafalcon 11 – Thales Underwater System (12 kHz), installed in 1995. The system can operate in two modes: bathymetry and imaging mode and sub-bottom profiler mode. The operation depth rage is 50 to 11,000 m. Five spatially separated cross-track swaths separated by an angle of 1.4° (along track separation) are simultaneously created in order to create data redundancy and avoid data gaps. The swath angle ranges from 120° - 140° depending on the water depth and signal-to-noise-ratio. The data was cleaned for outliers using Fledermaus-DMagic package and plotted using Generic Mappting Tools (GMT).

3.4. Seismic stratigraphy

Only 2 wells are located on the seismic profile BGR07-205. 5 prominent horizons were identified across all profiles excluding the basement and seafloor. Each of the seismic units bounded by the horizons are labeled MBSU-1 – MBSU-6 and were correlated to the litho-stratigraphic information of the wells. Although Zambezi-3 well was drilled only until Upper Cretaceous, deeper horizons were constraint by correlating the seismic interpretations of Mahanjane (2012)and Salazar et al. (2013) who used industry seismic profiles that overlap with our seismic profiles and additional well data on and off-shore that reached the basement. These profiles also helped in corroborating our identified horizons independently.

3.5. Palaeobathymetry

This section describes the methods used in my second manuscript using the results and interpretations of the first manuscript.

New oceanic crust subsides as it cools and moves away from the ridge and is loaded with sediments and water. There are several methods in which one may model past bathymetry where different factors are incorporated. In the second manuscript, we use backstripping technique introduced by Watts and Ryan (1976). It estimates palaeo-water depth by removing sediments younger than the reconstruction age, restoring the underlying sediments to its unloaded conditions (decompaction), incorporating the sea-level at that time and compensating for thermal subsidence of the lithosphere and isostatic adjustment. This is implemented with BalPal v0.9 (Wold, 1995) where user supplied data is used for setting boundary conditions. The following sections describe various stages for input data preparation and implementation of BalPal v0.9 that is not explained in the manuscripts.

3.5.1. Sediment compaction

Decompaction of sediments requires the knowledge of how porosity (p) changes with depth (z). Sediment porosity typically decreases with depth depending on initial conditions as overlying sediments and hydrostatic pressure compress and repack the underlying sediments. Empirical studies conclude that they can be expressed as exponential decay, power law or parabolic (Figure 3.7) (Bahr et al., 2001; Baldwin and Butler, 1985; Huang and Gradstein, 1990; Sclater and Christie, 1980). Mathematically these functions can be expressed as;

$p = A \exp(-B\,Z)$ -> exponential

$p = A - (B\,Z) + (C\,Z^2)$ -> parabolic

$p = 1 - A\,Z^B$ -> power-law

where A, B and C are constants to be determined for each sediment type.

Ideally, in-situ measurements of porosity give a more precise estimation of the compression factor. The accuracy of our palaeobathymetric models depend porosity values. However, due to lack of drill log data, we rely on global estimates for compaction of sediments and regional stratigraphy for lithology.

In BalPal v0.9, the stratigraphy determines the sediment thickness to remove and the lithology determines how the remaining sediments would decompact to the state before loading.

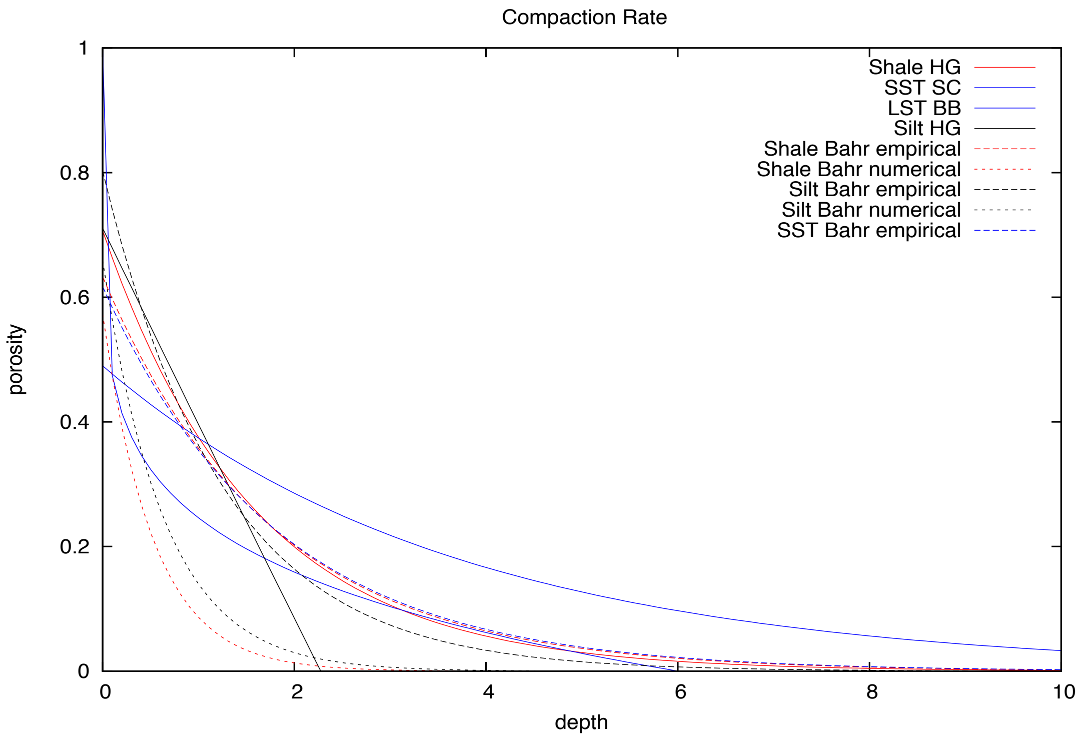


Figure 3.7: Porosity against depth relationship from various studies for sediment compaction rate estimation of different lithologies. Abbreviations: SST= Sandstone; LST= Limestone; Bahr=Bahr et al. (2001); BB= Baldwin and Butler (1985); HG= Huang and Gradstein (1990); SC=Sclater and Christie (1980)

3.5.2. Age Model

The global age grid model of Müller et al. (2008) is not sufficiently accurate in the study area with differences up to 8 Myr in Mozambique Basin and 5 Myr in the Riiser-Larsen Sea with respect to published magnetic magnetic anomalies identified by König and Jokat (2010) and Leinweber and Jokat (2012). The global age grid model was modified to fit the picked magnetic anomalies and the age for both margins were assigned from the Geological Timescale (Gradstein et al., 2012). The oldest identified magnetic anomaly is M25 is not located at the continent-ocean boundary. In this case the age was extrapolated until the margin to fit the age on its conjugate in the Mozambique Basin.

3.5.3. Thermal subsidence

Variations in seafloor depth and heat flow with age provide the main constraints on the thermal structure and evolution of the oceanic lithosphere. The thermal evolution of the lithospheric cooling as it spreads away from the mid-ocean ridges is expressed as a function of its age.

The GDH1 model assumes the following function for unperturbed seafloor younger than 70 Ma that is not affected by hotspots or oceanic plateaus.

$$z = 2600 + 365\mathrm{sqrt}(t)$$

where t is the age of the crust and z is the basement depth

and an exponential function for the observed depths of older oceanic lithosphere (seafloor flattening) :

$$z = 5651 - 2473 \exp(-0.0278t)$$

3.5.4. Isostacy

For backstripping, isostatic balance of the column is maintained above the isobaric surface (compensation depth) to compensate the effect of thermal subsidence and removal of sediments. Each column consists of water, sediment, crust and mantle layers. The total mass of the column (M) is required to be constant in order to achieve isostatic equilibrium. The depth of the isobaric surface is set to 100 km below present sea level. The height H_1 of a column is the sum of the thickness of the mantle T_M, crust T_C sediment T_S and water Tw:

$$H_1 = T_M + T_C + T_S + Tw$$

The total mass of the column is then

$$M = T_M \rho_M + T_C \rho_C + T_S \rho_S + T_W \rho_W$$

Where, ρ_M = *mantle density*
ρ_C = *crust density*
ρ_S = *sediment density*
ρ_W = *water density*

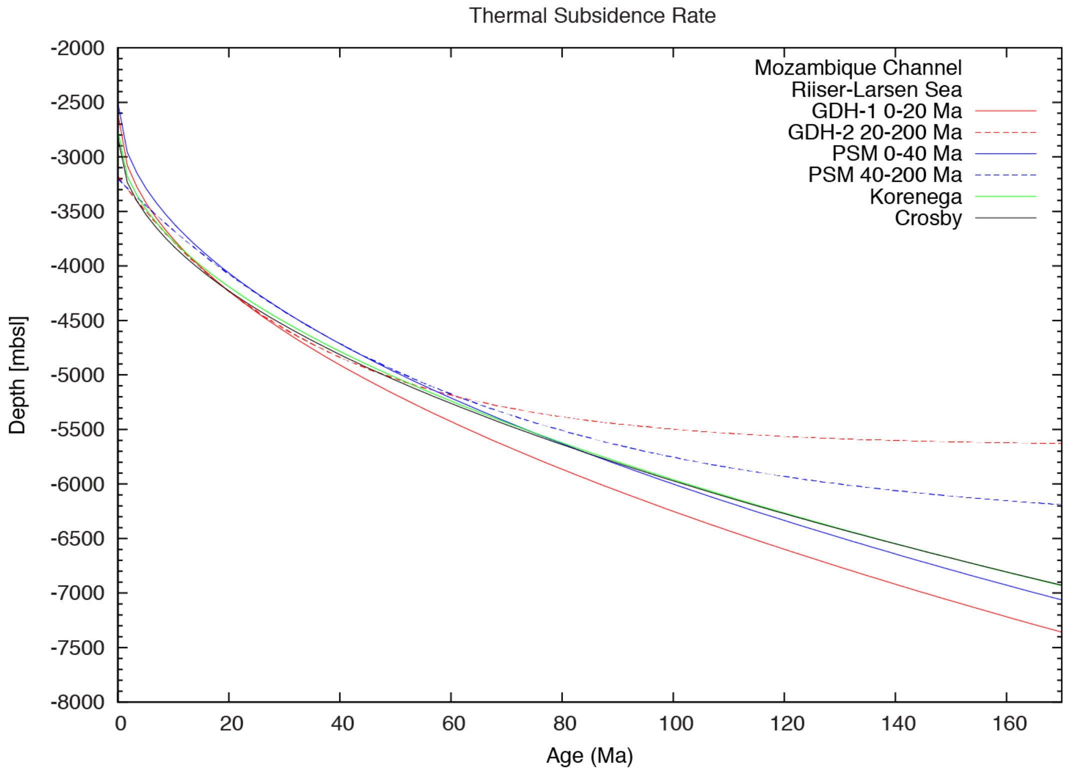


Figure 3.8:Age versus depth relationship for normal oceanic crust based on empirical data from different studies. (Crosby = Crosby et al., 2006; Korenega = Korenaga and Korenaga, 2008; PSM = Parsons and Sclater, 1977; GDH = Stein and Stein, 1992)

For a column at a younger age with different densities, the total mass should always be the same.

Therefore

$$T_{M1} \rho_{M1} + T_{C1} \rho_{C1} + T_{S1} \rho_{S1} + T_{W1} \rho_{W1} = T_{M2} \rho_{M2} + T_{C2} \rho_{C2} + T_{S2} \rho_{S2} + T_{W2} \rho_{W2}$$

For the backstripping, isostacy has two consequences: (1) Subsidence due to sediment loading (change in $T_S \rho_S$) and (2) subsidence related to densification of the lithosphere associated to cooling (change in ρ_M and ρ_C). Figure 3.9 shows a schematic sketch the effect for both cases.

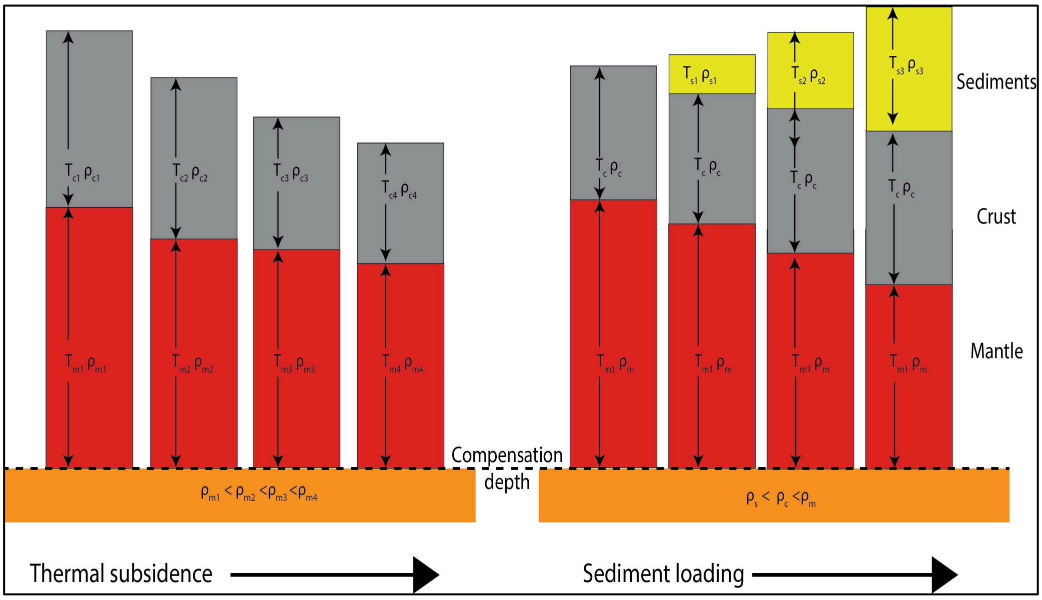


Figure 3.9: Isostatic compensation for thermal cooling and sediment loading.

Chapter 4: Mesozoic and Early Cenozoic sediment influx and morphology of the Mozambique Basin.

Authors:

Jude A. Castelino[1], Christian Reichert[2], Frauke Klingelhoefer[3], Daniel Aslanian[3], Wilfried Jokat[1]

[1]*Alfred Wegener Institute, Hemholtz Centre for Polar und Marine Research (AWI), Bremerhaven*

[2]*Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover*

[3]*Institut francais de recherche pour l'exploitation de la mer (IFREMER), Brest*

Journal of Marine and Petroleum Geology

doi:10.1016/j.marpetgeo.2015.07.028

Received 18 May 2015
Accepted 30 July 2015
Available online 1 August 2015
Published in print September 2015

Keywords

Multi-channel seismic, Mozambique Basin, Zambezi submarine fan, Beira High, seismic stratigraphy, Late Cretaceous uplift, low-velocity sediment layer, Late Cretaceous, bottom current, sediment drift bodies.

4.1. Abstract

The Mozambique Basin is one of the oldest extensional sedimentary basins developed along the eastern African margin. The basin hosts a continuous record of sediments since the Jurassic separation of Antarctica from Africa. The objectives of this study were to extend the regional stratigraphic framework north of the Zambezi Delta into the deep abyssal plains and review the early evolution of the Mozambique Basin using nine multi-channel seismic reflection profiles.

We identify six major stratigraphic units that were deposited in Jurassic, Early Cretaceous, Late Cretaceous, Paleogene, Neogene and Quaternary times. Mesozoic sedimentation rates of 5-10 cm/kyr and 1-3 cm/kyr during the Paleogene are calculated in the deeper basin. The presence of shales in neighbouring wells on the shelf implies an euxinic environment in the rapidly subsiding basin until Early Cretaceous times. The Mesozoic sediments have a high seismic velocity that exceeds 4.5 km/s, except in a distinct Early Cretaceous low-velocity (3.7 km/s) zone that may indicate the presence of undercompacted, overpressured shales. In spite of the fact that the Zambezi catchment was much smaller in pre-Miocene times, the high Late Cretaceous sedimentation rates can be attributed to rapid denudation of the African continent after a major tectonic uplift episode at approximately 90 Ma. Increased sediment influx into the basin from the Zambezi in Late Cretaceous times resulted in the formation of an elongated submarine fan lobe into the Mozambique Channel north of Beira High. Strong north-south bottom currents commenced within the channel in Late Cretaceous times, forcing the aggradation of sediments on the southern flank of the lobe. In addition, we observe several current-controlled sediment deposits in the deeper basin that are influenced by north-south bottom currents. Low Paleogene sedimentation rates are attributed to a sediment-starved basin during a relative quiet tectonic phase onshore.

4.2. Introduction

The separation of East and West Gondwana resulted in the formation of extensional sedimentary basins along the African margin (Jokat et al., 2003; König and Jokat, 2010; Mahanjane, 2012; Nairn et al., 1991; Reeves, 2000; Salman and Abdula, 1995). The Mozambique and Somali basins were the first basins to form along the east African margin (Coffin, 1992; Coffin et al., 1986; Leinweber and Jokat, 2012; Leinweber et al.,

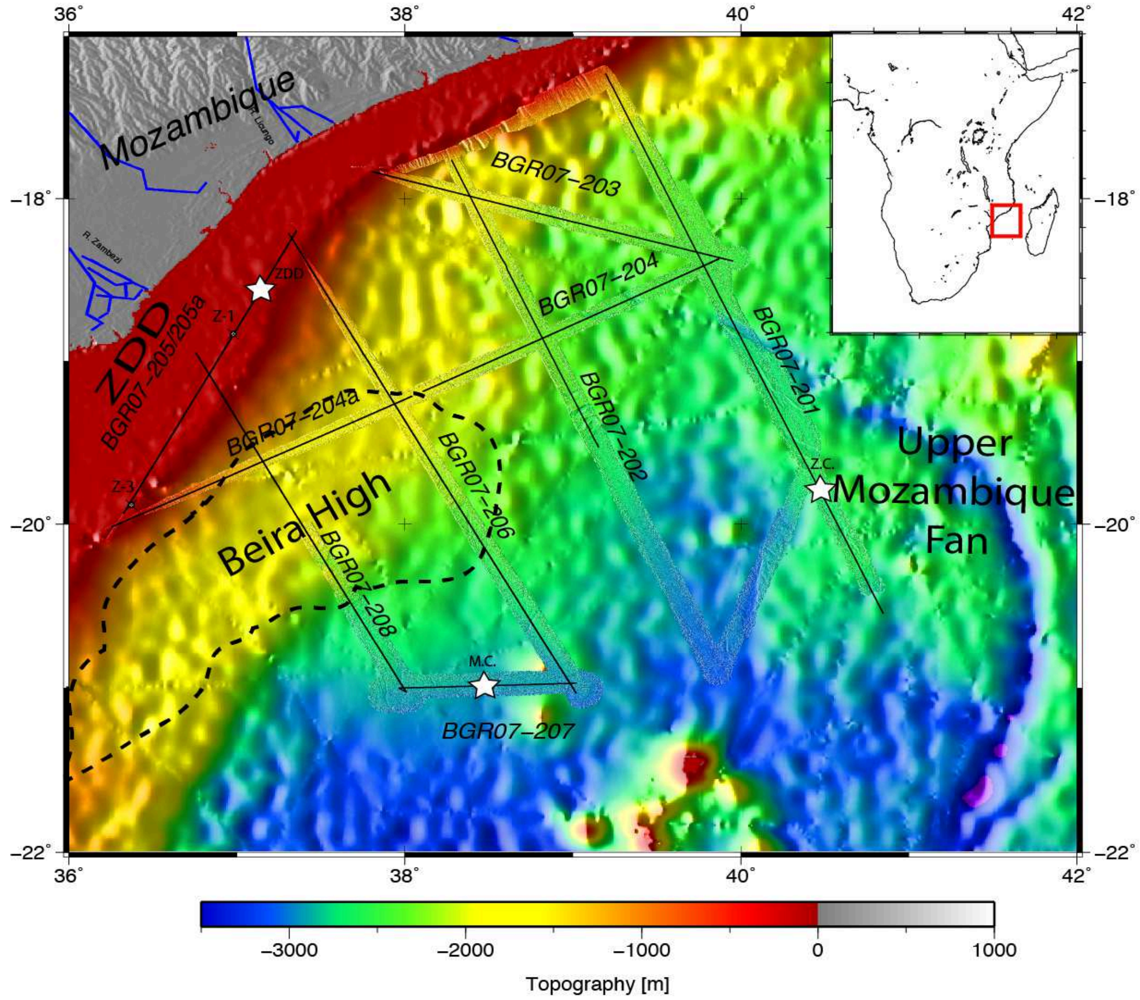


Figure 4.1:Bathymetric map of Mozambique Basin showing seismic reflection profiles (black) and drilling sites Zambezi-1 (Z-1) and Zambezi-3 (Z-3) in the Zambezi Depression Delta (ZDD) used in the study. Multi-Beam Echo Sounder (MBES) data from expeditions MD-163 (Reichert, 2007) are overlain on the GEBCO_08 grid. The locations of our calculated sedimentation rates are indicated by white stars; with permission from Elsevier

2013). Basin formation was complemented by eastward flowing rivers systems that transported large quantities of sediments into the newly formed depressions.

Most of the east African basins show a continuous post-Jurassic record of sediment deposition (e.g. Somali, Rovuma and Mozambique)(Coffin et al., 1986; Salman and Abdula, 1995). Sedimentary deposits contain a precious archive of past processes that shaped the landscape. Palaeo-reconstructions of Africa and the West Indian Ocean rely on the quantification of these events. Important information can be found in the Mozambique Basin, its northern neighbour the Somali Basin, and its Antarctic conjugate basin, the Riiser-Larsen Sea. Despite its importance, literature about the geological evolution of the Mozambique Basin is scarce.

Few seismic data are available in the abyssal plains of the Mozambique Channel (Droz and Mougenot, 1987). Commercial seismic data were mainly acquired on the shelf. This gap was closed in 2007 when different seismic/geophysical data were collected with R/V Marion Dufresne II as part of the MD163-MoBaMaSiS expedition (Reichert, 2007) (Figure 4.1). These data included reflection and wide-angle seismic data, as well as gravity, magnetic and bathymetric data. The expedition aimed to collect data that could be used to understand the continental break up and geological history of the basin. Here, we introduce a stratigraphic interpretation of the multi-channel reflection seismic (MCS) data acquired during the expedition. We discuss the influence of former geological events on the changing environmental settings during the break-up in the Mesozoic and try to quantify the amount of the material eroded from the Eastern Africa.

4.2.1. Tectonic and geological setting

The break up of Gondwana has been described as a two phase process by several authors (Cox, 1992; Eagles and König, 2008; Leinweber and Jokat, 2011; Mahanjane, 2012; Reeves, 2000). The seafloor spreading record in the Mozambique Basin can be quite simply interpreted in terms of the divergence of Africa and Antarctica. As seen from a fixed Africa, initial rifting in Early Jurassic times occurred in response to southwest-directed motion of Antarctica. This displacement was followed by southward relative movement during the second phase. The palaeo-position of Madagascar is important for the geological history of the region. Although long a subject of debate (Flores, 1984; Foerster, 1975; Kamen-Kaye, 1982), it is now widely accepted that Madagascar drifted southwards from Tanzania along the Davie shear zone (Rabinowitz et al. 1983; Coffin, 1987) or Davie Ridge Transform fault system *(referred to with different names by various authors)*. During its drift phase, Madagascar moved southwards with seafloor spreading in the Somali Basin until some time during the Early Cretaceous (M10n or M0, 129.5 or 118Ma). The island has occupied its present position as part of the African plate since the termination of seafloor spreading in the west Somali Basin (Cochran, 1988; Eagles and König, 2008; Rabinowitz et al., 1983; Salman and Abdula, 1995) .

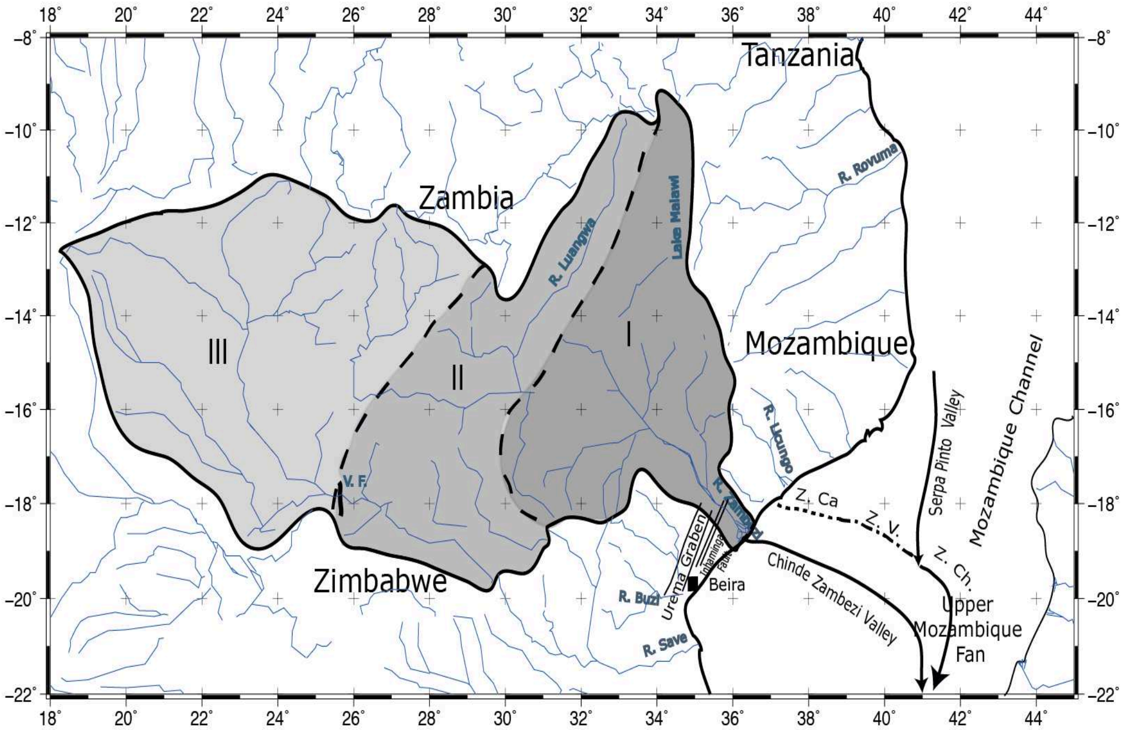


Figure 4.2: Catchment area of the Zambezi River and feeding paths in the Mozambique Channel. The present catchment area of the Zambezi River is displayed as grey shaded area. The dotted lines indicate the boundaries of Early Cretaceous (I), Late Cretaceous (II) and present-day (III) catchment areas of the Proto-Zambezi River (modified from Walford et al, 2005). Abbr: Z.Ch = Zambezi Channel, Z.Ca= Zambezi Canyon, Z.V.= Zambezi Valley; with permission from Elsevier

Onshore, the African topography is interpreted as a product of complex cycles of erosion (Burke, 1996; Patridge & Maud, 1987 and references therein). Patridge & Maud, (1987) suggest a single Jurassic-to-Miocene cycle of erosion briefly interrupted by tectonic interludes. Most of the erosion occurred in the earlier part of the above time interval resulting in the deposition of thick Jurassic and Cretaceous strata offshore. Regional uplift may have accompanied intense magmatism between 90 -70 Ma in southern Africa (Burke, 1996). This is evident from the rapid denudation and thick Upper Cretaceous deposits along the Limpopo Valley (De Buyl and Flores, 1986), at the mouth of the Orange River (Miller, 1995; as cited in Burke, 1996), and in the increased sediment discharge of the Zambezi (Walford et al., 2005). Among the major rivers that drain into the Mozambique Basin are the Zambezi and its tributaries that are responsible for the wide continental shelf along the Mozambique coast. The present Zambezi has a catchment area of 1,400,000 km^2. The sediment load of the Zambezi River is estimated to have increased by an order of magnitude in the last 120 Ma (Walford et al., 2005).

They assume that sediment yield rates depend on basin area and maximum elevation. The modern Zambezi system is thought to have developed from two drainage systems separated by the Victoria Falls – Upper Zambezi and Middle Zambezi. They merged no earlier than Pliocene times (Nugent, 1990; Thomas and Shaw, 1988) and thereby increased the sediment discharge of the Zambezi. Prior to that, the Upper Zambezi is proposed to have continued its southerly course into Botswana and into Orange or Limpopo river drainage systems. Increases in sediment flux from the Zambezi River are observed over 3 periods:

1. Since Late Cretaceous (90-65 Ma): simultaneous with rapid denudation of southern Africa after a tectonic uplift and increase of the catchment area.
2. During Late Oligocene- Early Miocene times (30 -23 Ma): caused by uplift of Africa by 300-500 m.
3. Since Late Miocene (5 Ma): the flux is still rapidly increasing, because of doubling of the Zambezi catchment area since Pliocene (Figure 4.2) (Walford et al, 2005) and an regional uplift of 900 m (Partridge and Maud, 1987).

4.3. Methods

4.3.1. Data Acquisition

Nine MCS profiles were recorded from August to September, 2007 off Mozambique with the French research vessel Marion Dufresne II - MD 163 (Reichert, 2007). A 3000 m streamer with 240 active channels and group spacing of 12.5 m was towed 150 m behind the ship. A seismic source consisting of five G-guns (8.5 l) with a total volume of 42.6 l at a pressure of 145 bar were used for acquiring the seismic reflection profiles and 8 G-guns (total 67.2 l) with 30 ocean-bottom seismometers and 10 land stations to gather wide-angle seismic data. For most of the MCS lines a shot interval of 18 seconds at a speed of 5.4 knots provided a shot spacing of 50 m. For acquiring the seismic refraction profiles, a shot interval of 60 seconds was used. Since the streamer acquired the seismic reflection data coincident with the refraction data, the larger shot interval resulted in a lower fold. In order to achieve a balance of high resolution and sufficient fold, the seismic reflection profiles were processed with a common depth point (CDP) spacing of 12.5 m, while seismic reflection profiles acquired parallel with the deep seismic sounding data were processed with a CDP spacing of 50 m.

4.3.2. Data processing:

The raw recorded data were demultiplexed and edited for static correction before sorting them in 12.5/50 m bins. In addition to the standard seismic processing workflow, all profiles were processed for multiple suppression in two steps:

- Surface related multiple attenuation (SRMA).
- f-k filter / Deconvolution.

The profiles were frequency filtered (10 - 60 Hz) and stacked using a median stack. Subsequently they were migrated using a F-K algorithm.

Prominent horizons were used for stratigraphic correlation controlled by results from the Zambezi-1 and Zambezi-3 well data (De Buyl and Flores, 1986) and previous studies (Mahanjane, 2012; Salazar et al, 2013; Salman & Abdula, 1995).

Interpreted sections of the seismic data were converted from Two-Way Travel (TWT) time to depth using velocity models created from Normal-Moveout (NMO) analysis of MCS data and controlled by the results of the wide-angle velocity model.

Bathymetric data shown in this study were gathered along the entire cruise track. The data from the MoBaMaSiS project were acquired using hull-mounted Seafalcon 11-Thales underwater system (12 kHz). Processing was done on using Fledermaus - DMagic software package. Sediment thickness and depth to basement were interpolated over the study area using a Kriging algorithm.

4.4. Results

The seismic profiles are oriented in a NW-SE and NE-SW direction along the spreading direction that provides adequate coverage of the entire basin. Four profiles are located to the north of Beira High while three MCS profiles cross Beira High. One profile crosses the Zambezi-1 and Zambezi-3 wells for age control for the seismic network. Table 4.1 shows the general stratigraphy of the region compiled from onshore and offshore wells. The well data were described by De Buyl and Flores, (1986) and Salman and Abdula, (1995).

The general structure and seismic expression of each seismic unit in the survey region is given in Table 1, and in the following section.

Sediment	Age		Seismic expression	Composition / Formation		Environment / Events
MBSU- 6	Quaternary	Holocene Pleistocene	Prograding clinoforms, Channel- levee system in the south, Continuous strong reflectors	Marine deltaic sediments		Third tectonic Uplift. Downslope sediment deposition process and formation of submarine canyons
MBSU- 5	Miocene Oligocene		Prograding clinoforms, Continuous strong reflectors. Underlain by unconformity	Marine deltaic sediments – Jofane Formation Temane Formation		Southern African Uplift. Oligocene marine regression
MBSU- 4	Eocene Paleocene		Strong continuous reflectors, Current-controlled deposition	Marine deltaic sediments – Cheringoma and Inharrime Formation		
MBSU- 3	Upper Cretaceous	Maastrichtian Campanian Santonian Coniacian Turonian Cenomian	Strong continuous parallel reflectors.	Grudja Formation Upper Domo shales Formation		Late Cretaceous volcanics. Tectonic Uplift of southern Africa.
MBSU- 2	Lower Cretaceous	Albian Aptian Neocomian	Strong parallel reflectors	Sena Formation	Lower Domo shales Formation Maputo Formation	Euxinic marine environment
MBSU- 1	Late Jurassic		Strong chaotic and discontinuous reflectors	Continental red beds and salt layers		
Basement	Middle –Late Jurassic		deformed by extension, strong hummocky reflectors	Karoo igneous		Rifting, Opening of Mozambique basin

Table .4 1.: Seismic stratigraphy of the Mozambique Basin used for the interpretation of the seismic profiles in this study. The ages of the seismic units are derived from wells located on the shelf (Figure 4.1). Deeper horizons are modified from Mahanjane (2012) and Salazar et al. (2013). The composition and environmental condition are compiled from various publications.

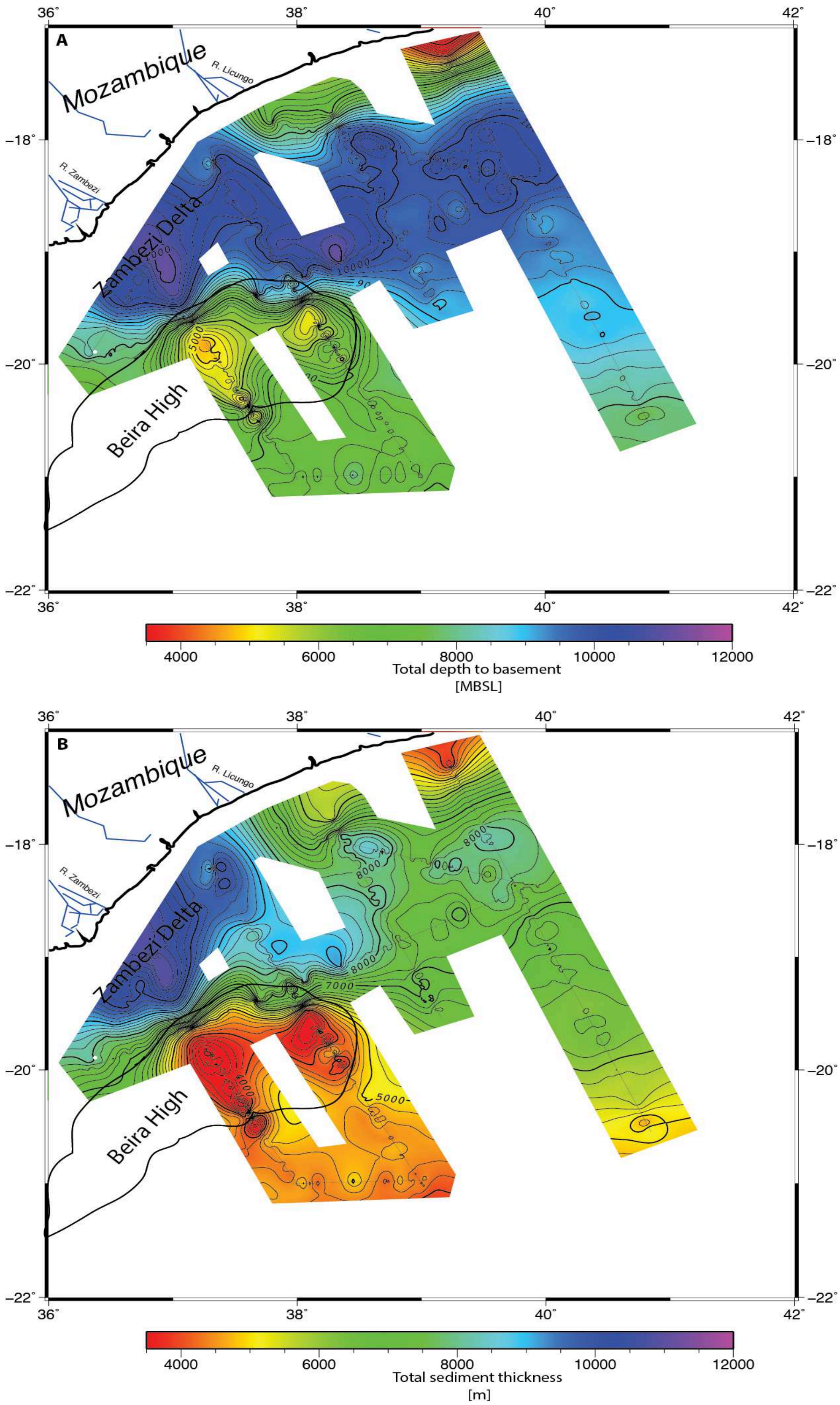


Figure 4.3: (a) Total depth to basement (mbsl) interpolated from our seismic profiles. (b) Total sediment thickness (meters) from interpreted seismic profiles; with permission from Elsevier.

4.4.2. Basement

The top of basement is identifiable from moderately strong reflectors underlying weakly reflecting sediments in most profiles. However, the basement reflectors are difficult to identify in the data in the Zambezi Delta Depression. With the exception of Beira High, the basement topography ascends gently to the SSE away from the continent. The depth to basement varies between 7 and 11 km (Figure 4.3a). The deepest part of the basement coincides with the oldest oceanic crust (M41) and its juxtaposition with the Continent-Ocean Transition zone (COT) (Leinweber and Jokat, 2012) (Figure 4.4). Under the shelf, the basement dips steeply at ~6.8°, marking the COT. Beira High is a basement high with an average elevation of ~2 km relative to abyssal plains and ~4 km relative to the Zambezi Depression Delta (ZDD). Several minor faults characterize the oceanic basement. On the eastern flank of Beira High (Outer Beira High) major normal faults are observed that form graben-like structures. Local basement highs are observed on profiles BGR07-203 (Figure 4.6; SP 3600-4000) and BGR07-204 (Figure 4.7; SP 1200 – 1650).

4.4.3. MBSU-1

MBSU-1 comprises of Jurassic sediments most likely of terrestrial origin. It is characterized by a set of strong parallel reflectors overlying a slightly faulted basement (Figures 4.4-4.7). Below the shelf, the reflectors have a divergent pattern and onlap the basement (Figures 4.4-4.5; profile BGR07-201: SP 1-100, profile BGR07-202: SP 1200 – 1268). A more continuous and parallel pattern is observed in the deeper oceanic basin (e.g. profiles BGR07-203 (Figure 4.6; SP 3600-4000) and BGR07-204 (Figure 4.7; SP 1200 – 1650). The thickness of MBSU-1 decreases from 1800 m in the continent-ocean transition (COT) zone to 1300 m in the deeper basin. The depositional pattern differs around Beira High. West of the high, in the ZDD, the reflectors are less continuous; on the seaward side they are continuous and well stratified. The interface between MBSU-1 and the basement in most parts is defined by a strongly reflecting chaotic pattern. MBSU-1 drapes the basement around Beira High, while it fills the rift grabens on the outer Beira High (Figures 4.8,4.9), which is described as pre-rift unit by Mahanjane (2012). To the east of Beira High, the sediment layer is relatively thin in comparison to the western part. Most reflectors terminate with a folded onlap on Beira High (e.g. profile BGR07-206 - SP 4500, profile BGR07-208 - SP 1300).

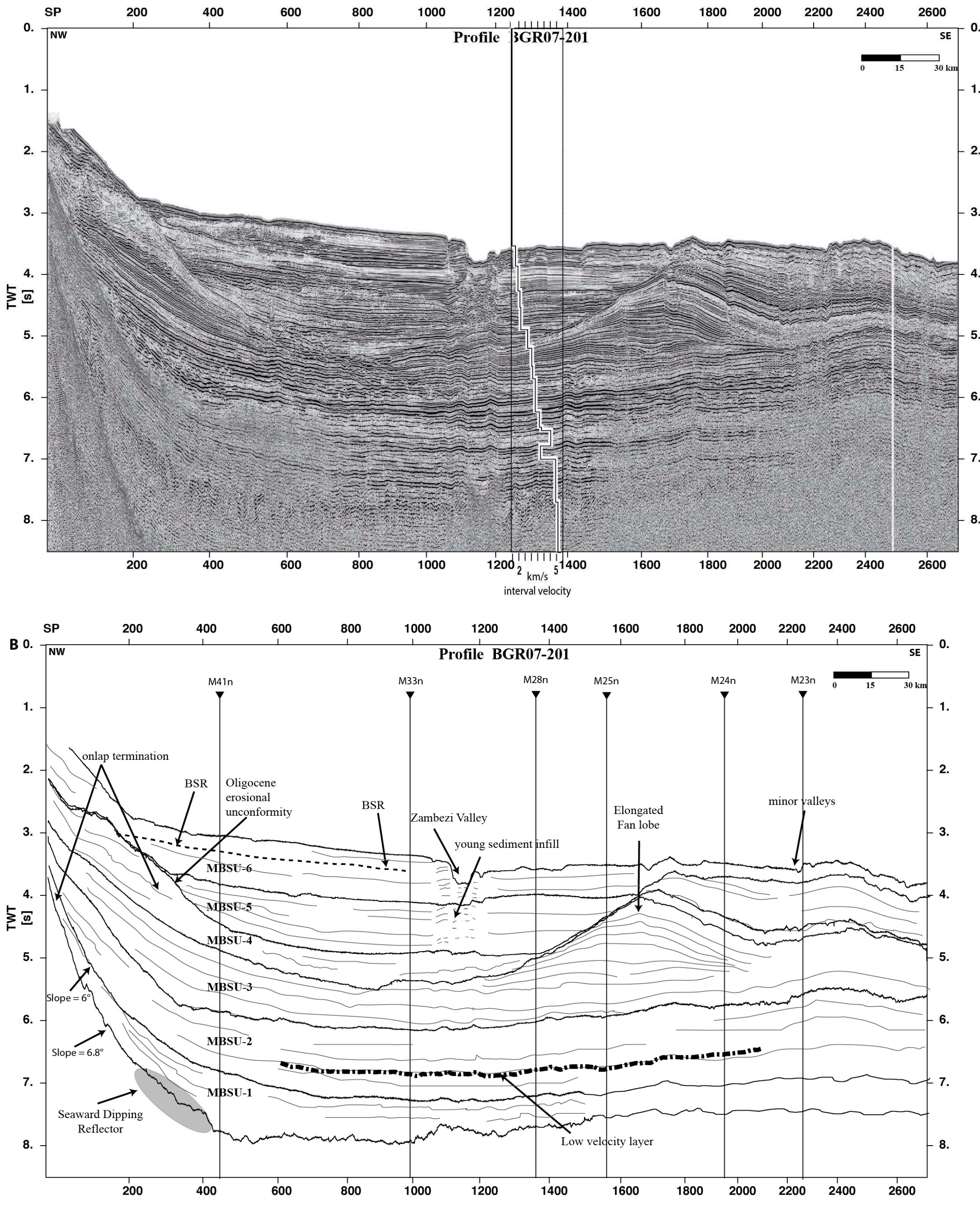


Figure 4.4: (a) Seismic reflection profile BGR07-201 with sediment interval velocity computed from NMO analysis indicated and (b) the interpreted section showing major features and sediment units with locations of magnetic anomaly identified by Leinweber et al. (2012). Seismic signals with reversed amplitude (BSR) are observed at the base of the continental slope (dashed line). A distinct low velocity zone with a strong amplitude is observed in MBSU-2 at ~6.5 s (TWT) (black dashed-dotted line) ; with permission from Elsevier.

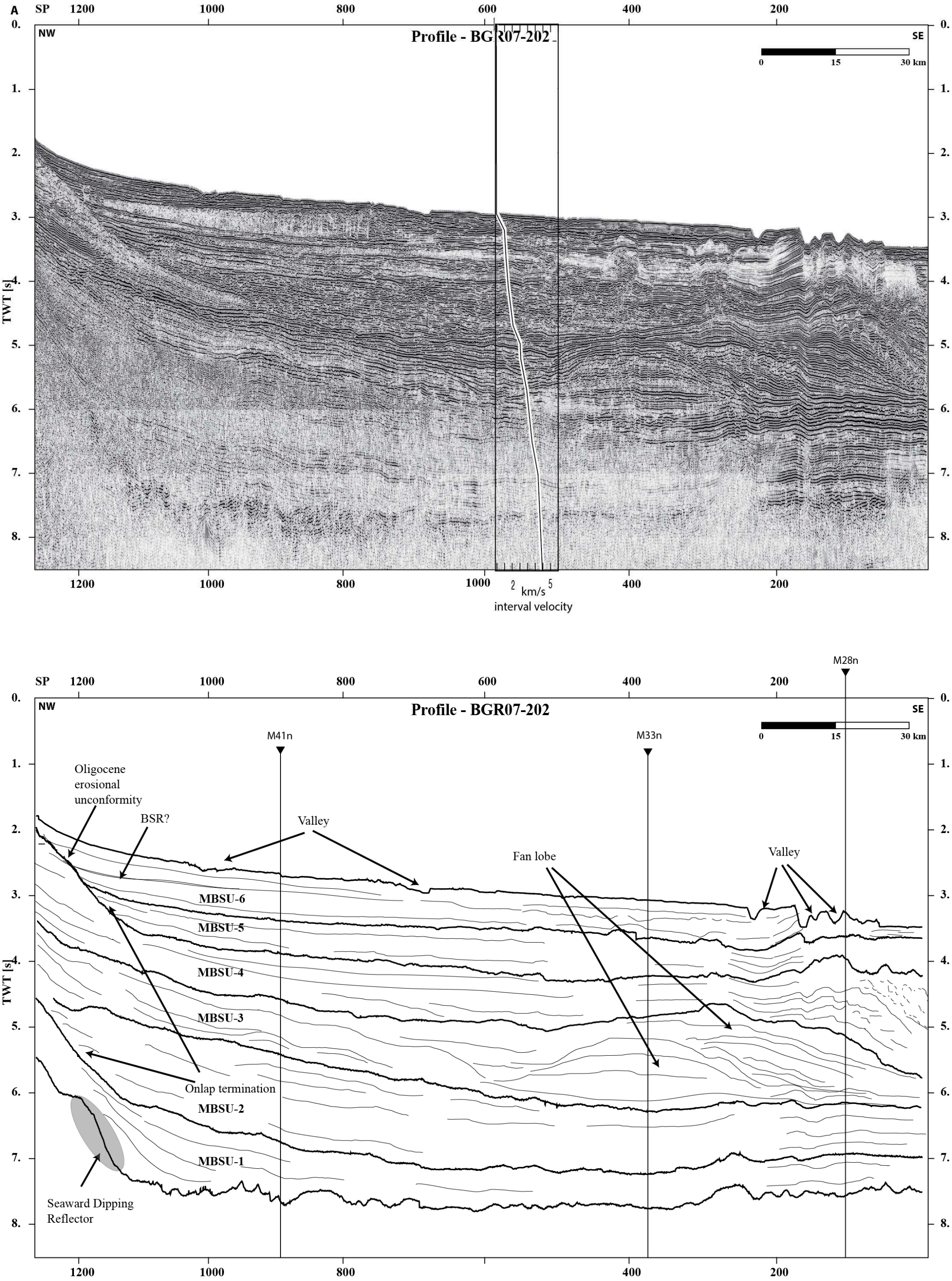
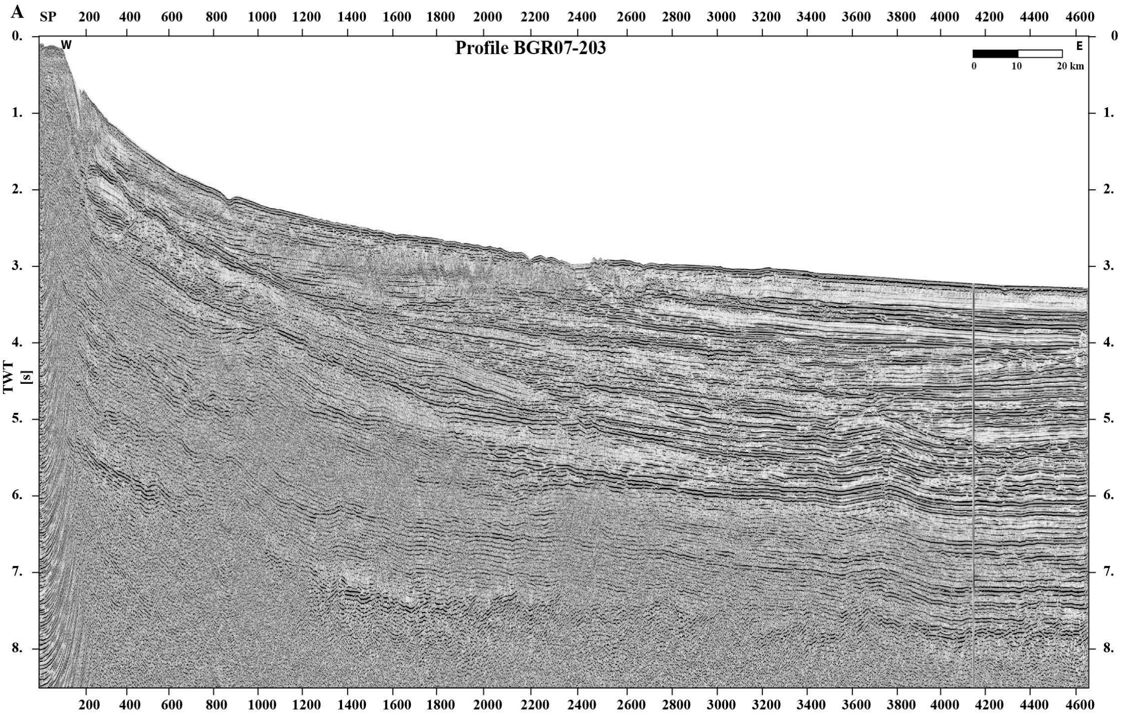


Figure 4.5: (a) Seismic reflection profile BGR07-202 with sediment interval velocities indicated and (b) the interpreted section showing major features and sediment units with locations of magnetic anomaly identified by Leinweber et al., (2012). On the shelf slope a distinct erosional unconformity with onlapping younger sediments is observed. A fan lobe (sediment wedge) that migrates to the southeast is observed within MBSU-3; with permission from Elsevier.



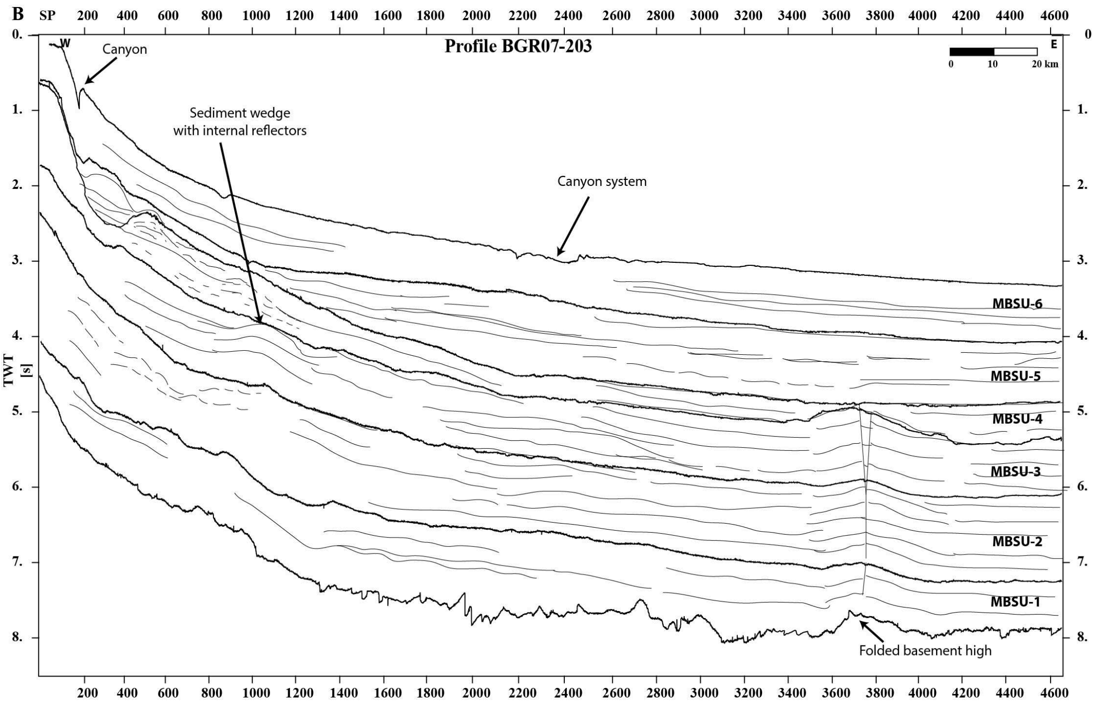


Figure 4.6: (a) Seismic reflection profile BGR07-203 and (b) line drawing showing major features and sediment units. Note a local basement deformation between SP 3600 -4000. The lowest three sediment units viz., MBSU-1 – MBSU-3 are interpreted to have deformed with the basement to produce anticlines. A submarine canyon incises the seafloor on the slope, which is a typical feature in the region; with permission from Elsevier.

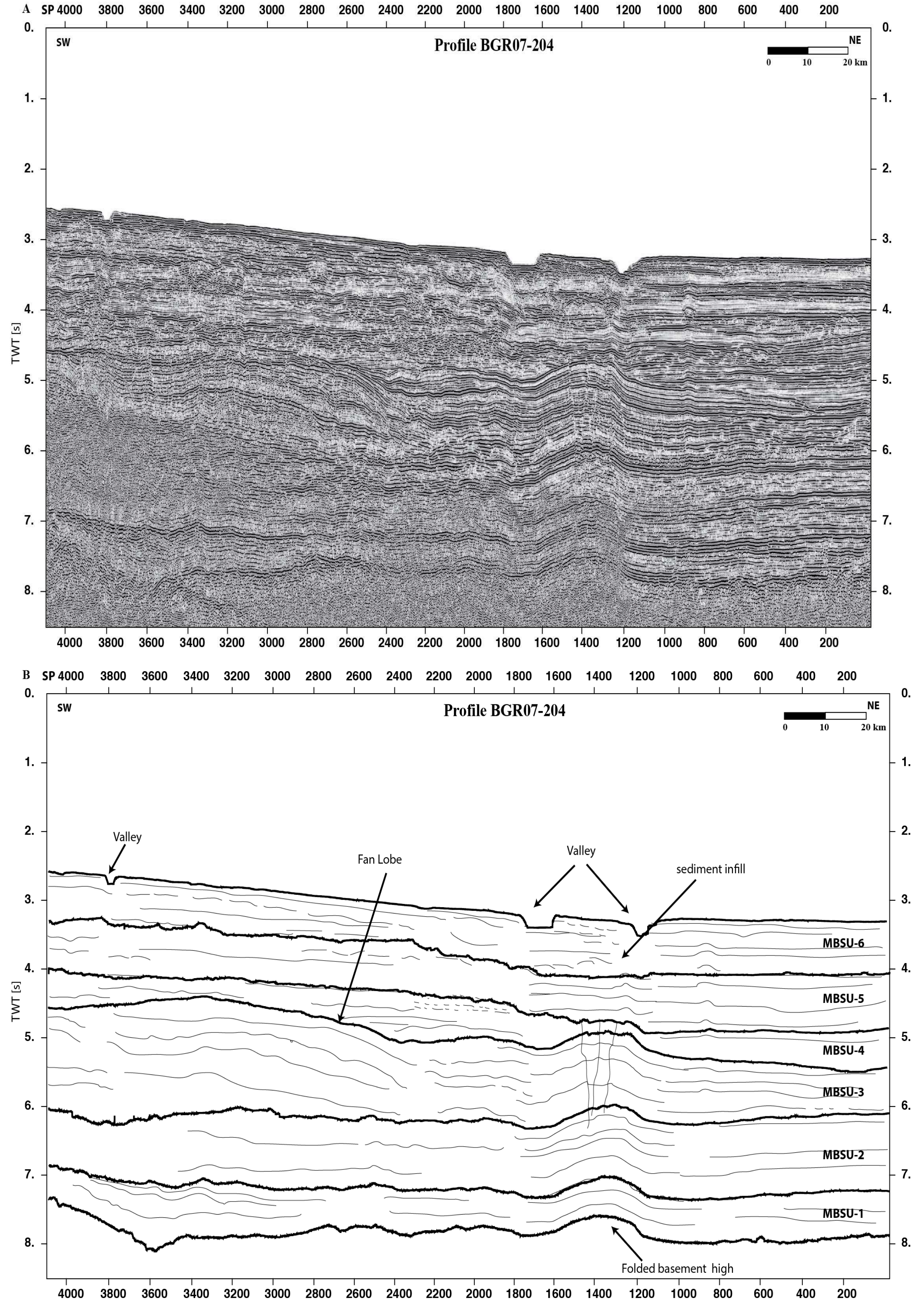


Figure 4.7: (a) Seismic reflection profile BGR07-204 and (b) line drawing showing major features and sediment units. Two major tributary valleys with infilled sediments join the Zambezi valley. A stack of anticlines like that in BGR07-203 is also seen in this profile; with permission from Elsevier.

4.4.4. MBSU-2

MBSU-2 consists of Early Cretaceous sediments. Several strong reflectors that are continuous and parallel define MBSU-2 (Figures 4.4-4.7). The thickness is almost constant and exceeds 2000 m in the basin. MBSU-2 is characterised by a distinct high amplitude low velocity zone in the northern part of the survey area. This low velocity zone is only 0.15 s TWT thick (Figure 4.4). MCS data indicate an interval velocity of 3.7 km/s for the low velocity layer, in contrast to 4.5 km/s for the overlying and underlying layers. Leinweber et al (2013) independently calculated a similar velocity contrast. There are very few or no sediments on top of Beira High from MBSU-2 (Figures 4.8; 4.9).

4.4.5. MBSU-3

MBSU-3, like the underlying units, is defined by strong reflectors that onlap against the underlying units under the shelf. However, wedge-shaped features with internal reflectors are observed at several locations in this sequence. In profiles BGR07-202 and BGR07-203, the wedge is located at the start of the proto-continental-rise (Figure 4.5, SP 750-1250; Figure 4.6; SP 800-1000). The other sediment wedges have a similar width and are located approximately along a West-ESE trending line (Figure 4.4, SP 900-2100; Figure 4.5, SP 150-600; Figure 4.7, SP 2200-3900). MBSU-3 is the uppermost unit to exhibit folding over the local basement high in profiles BGR07-203 (Figure 4.6, SP 3600-4000) and BGR07-204 (Figure 4.7, SP 1200 – 1650). Several normal faults offset the slightly folded sediment layers, some of which extend down to the oceanic basement. The sediment depocentre is located to the northeast of the present-day Zambezi mouth (Figure 4.11c). In the northwest, a prograding clinoform is observed (Figure 4.8, profile BGR07-206 - SP 1-800). Several sediment waves and faults are observed in the W-E oriented profile BGR07-207 along with an increase in sediment thickness towards the east in the abyssal plain where the gradient ascent away from Beira High is approximately 0.5° (Figure 4.8, profile BGR07-206 - SP 4800 – 7200)

4.4.6. MBSU-4

MBSU-4 is characterized by strong parallel reflectors. The observed thickness varies in the basin. The unit eventually pinches out towards the southeast. A prominent discontinuity coincides with the top of MBSU-4 and under the shelf, the reflectors are

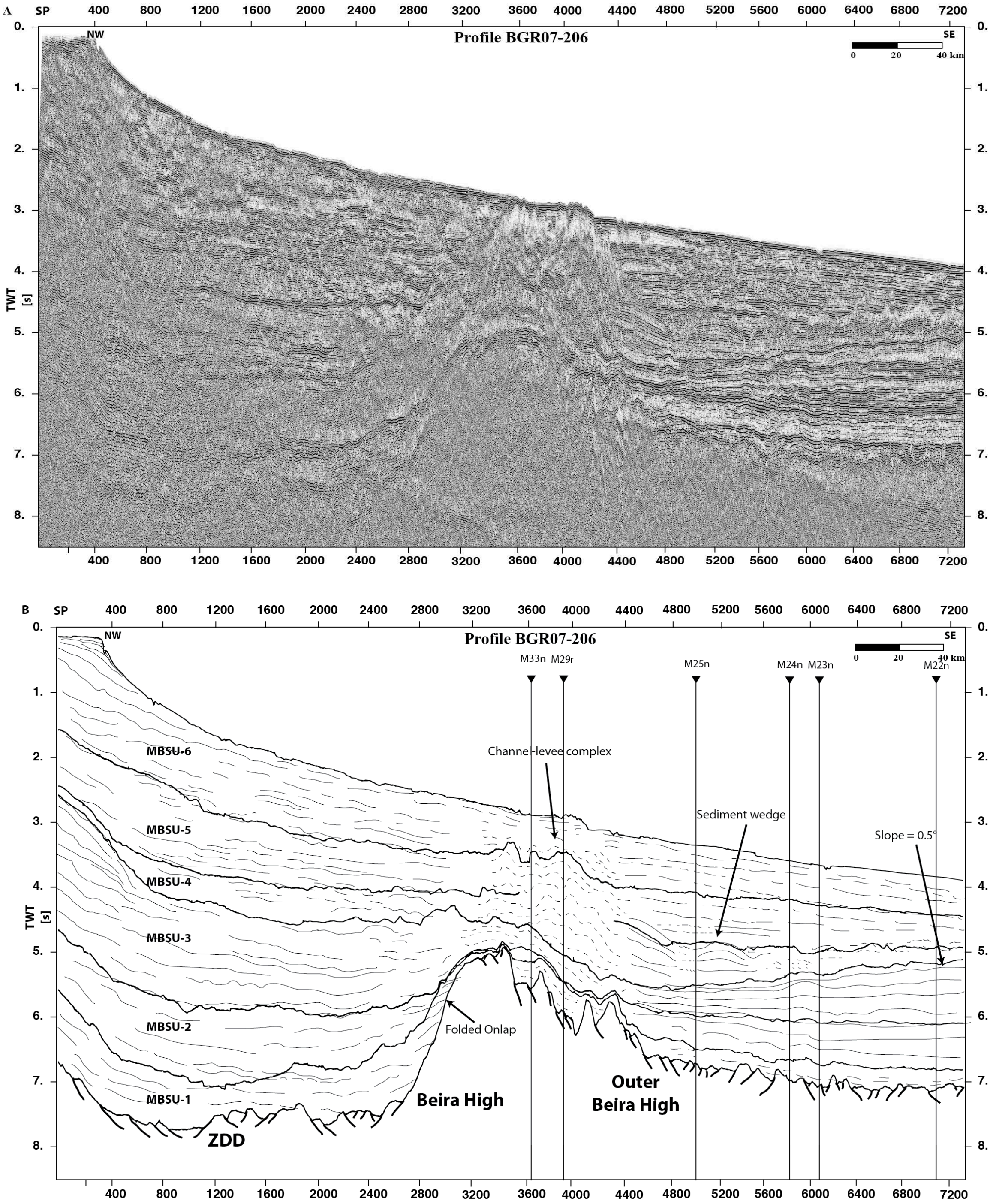


Figure 4.8: (a) Seismic reflection profile BGR07-206 that crosses the Beira High in the North and (b) the interpreted section showing major features and sediment units with locations of magnetic anomalies identified by Leinweber and Jokat (2012). MBSU-1 and MBSU-2 appear as thin layers across the Beira High or fills the grabens in the rifted basement. A well-developed channel-levee complex is seen above Beira High. MBSU-3 is a well-stratified unit dipping towards Beira High indicating a sediment source to the NE; with permission from Elsevier.

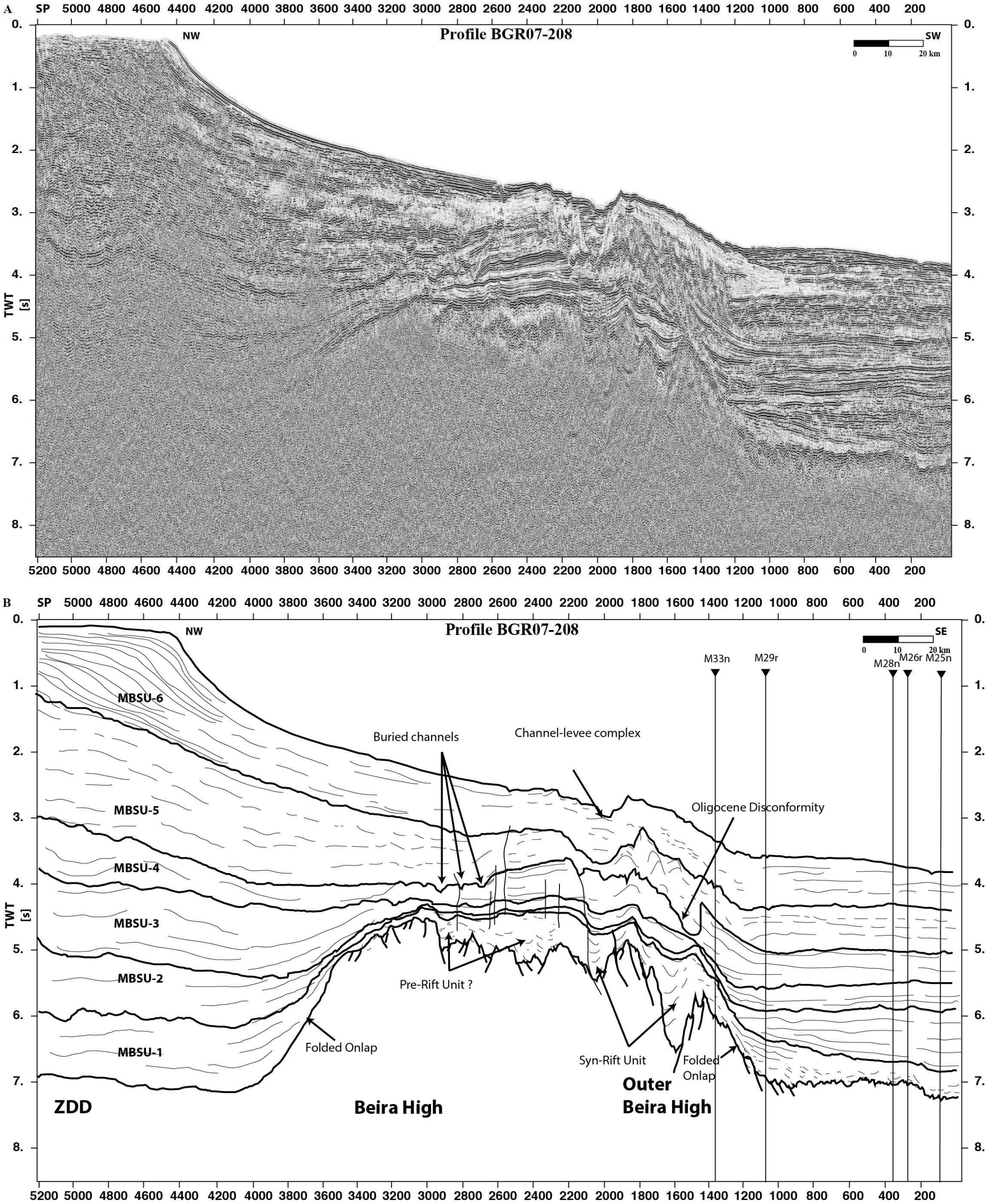


Figure 4.9: (a) Seismic reflection profile BGR07-208 across Beira High and (b) the interpreted section showing major features and sediment units with locations of magnetic anomalies identified by Leinweber and Jokat (2012). The Oligocene disconformity represents the erosion of Eocene sediments subsequently filled by Miocene sediments. Several buried channels are observed above Beira High at the top of MBSU-4, but only a few are labelled; with permission from Elsevier.

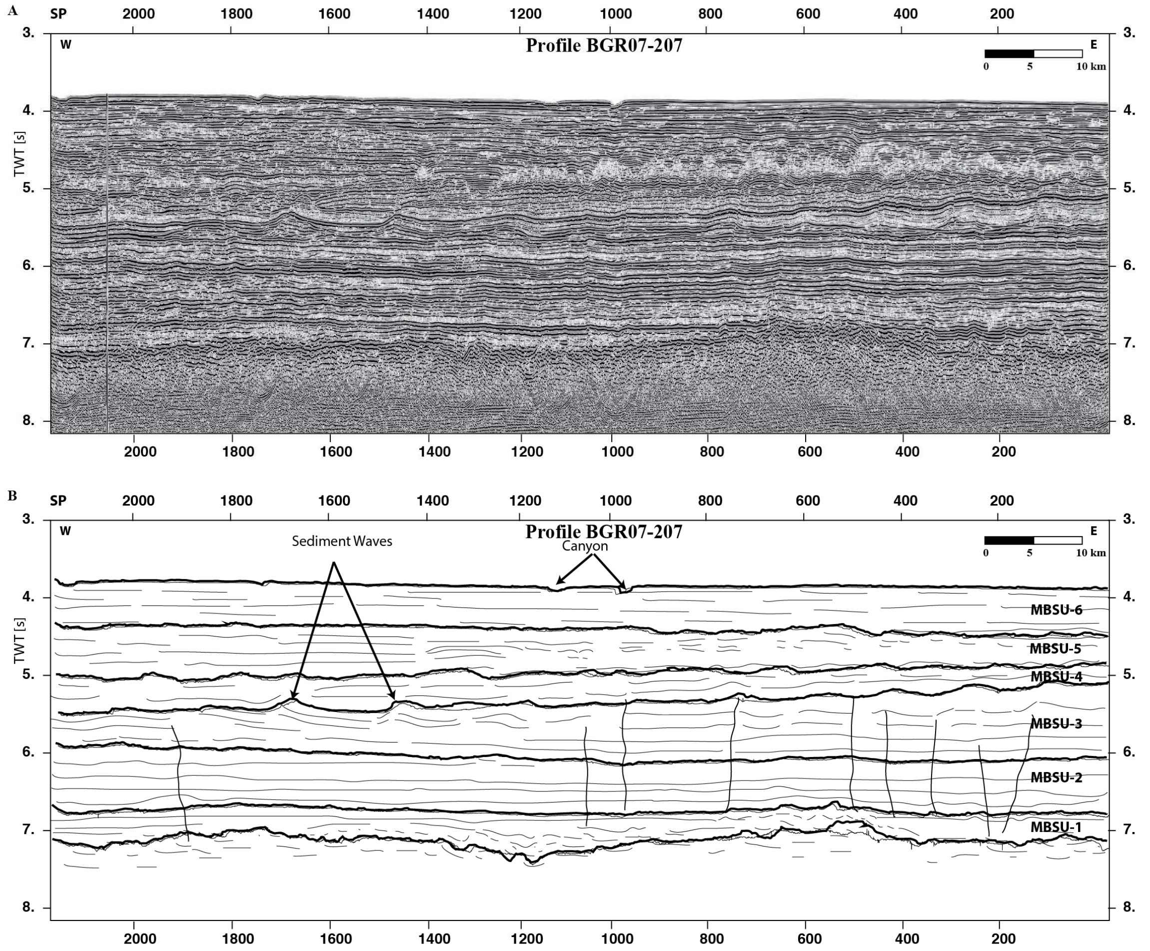


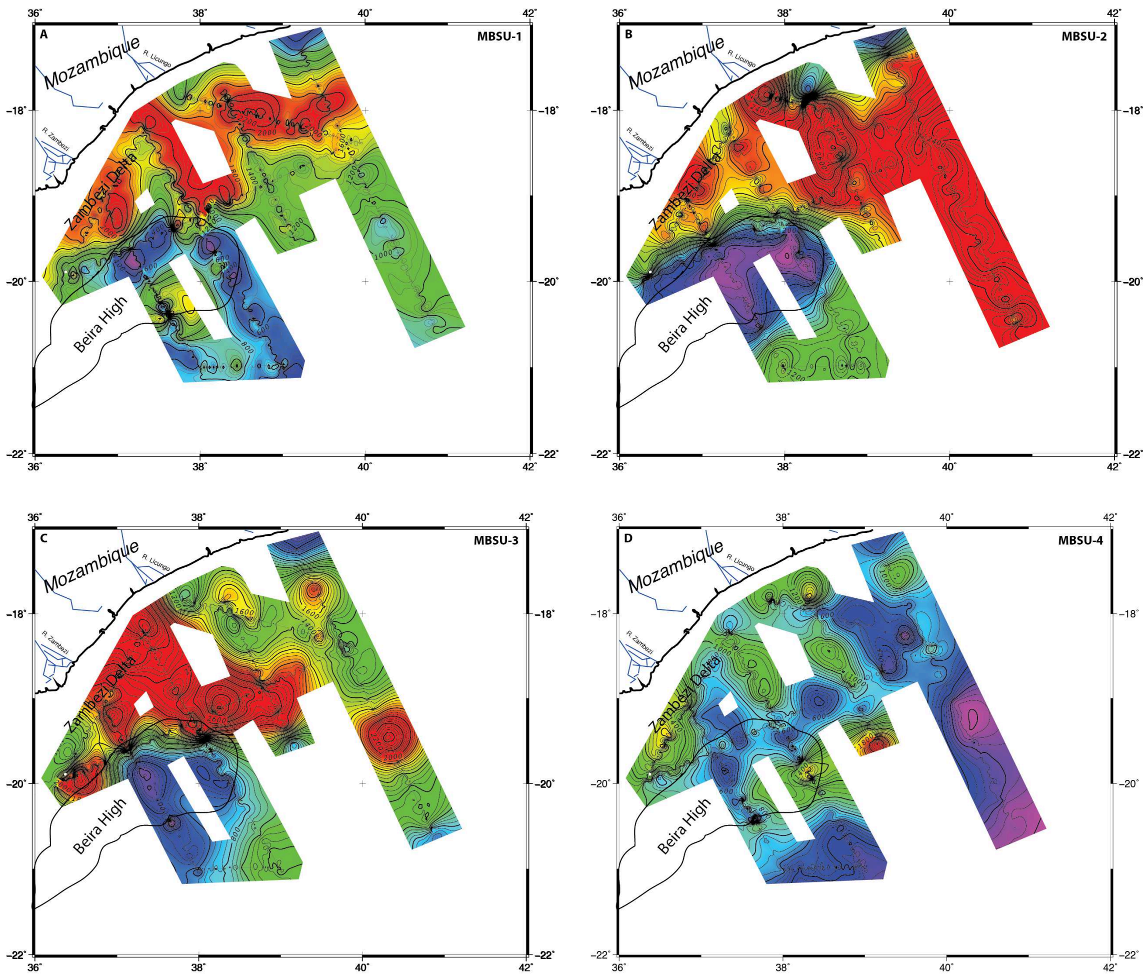
Figure 4.10: (a) Seismic reflection Profile BGR07-207 and (b) the interpreted section showing major features and sediment units. The sediment waves are exxagerated in figure 1.13a; with permission from Elsevier

truncated against the overlying unit (Figure 4.4, SP 150 -300; Figure 4.6, SP 1 -800). MBSU-4, in contrast to other units, is observed to be thinnest in most parts of the basin (< 0.5 s TWT) with an exception on the shelf in the south (Figure 4.11d, profile BGR07-208 - SP 4000 - 5183). The top reflector of MBSU-4 cannot be traced over the outer Beira High where it is heavily eroded and replaced by younger sediments of the channel-levee system (Figures 4.8,4.9; profile BGR07-206 - SP 3800-4300; profile BGR07-208 - SP 1200-2100). In the ZDD, younger sediments have also filled several smaller palaeo-channels.

4.4.7. MBSU-5 and MBSU-6

The seismic character of the upper two units varies strongly within the deeper part of our study area. MBSU-5 and MBSU-6 primarily fill the depression between the sediment wedge in the south and the shelf further northwest. While MBSU-5 and MBSU-6 appear as thick well-defined prograding sequences on the shelf in the ZDD, they are conspicuously insignificant on the northern shelf. On the slope and at the beginning of the continental rise, the seismic character is patchy with a hummocky pattern. In the deeper parts of the basin, packages of continuous and almost parallel reflections alternate with weak and strong amplitudes.

Several shallow valleys cut into the seafloor. One of the most prominent valleys is the deep sea Zambezi Valley, which is observed in the profile BGR07-201 (Figure 4.4, SP 1100-1200). Here, the valley is bounded by major faults forming steep side walls, and hummocky-chaotic sediment bodies lie on its floor. Reflector expressions are similar on either side of the valley. A system of submarine channels is observed in the southeast of profile BGR07-202 (Figure 4.5, SP 50-250). The reflector characteristics distinctively change below the channel. Faults penetrate the uppermost three seismic units. Two



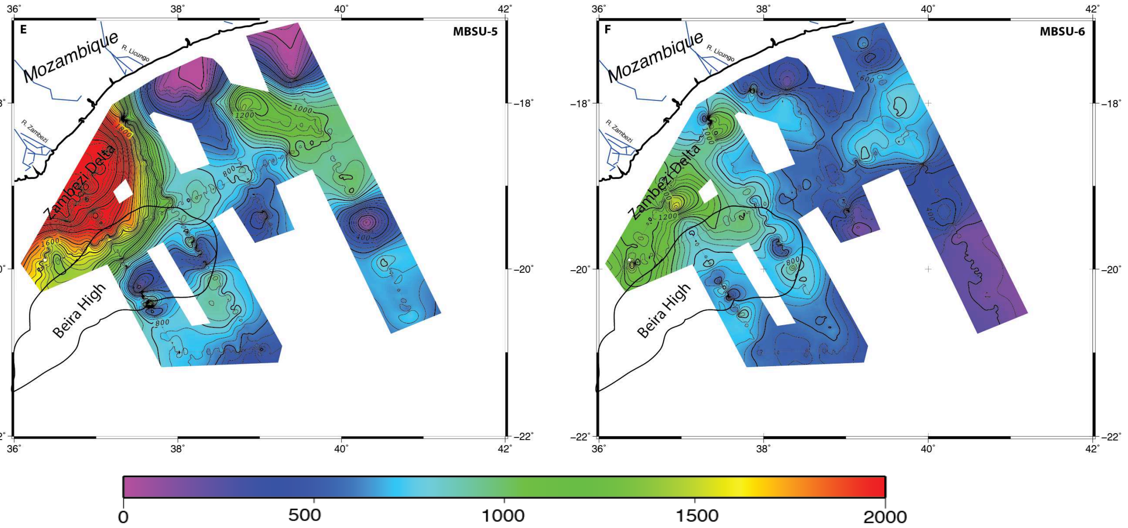


Figure 4.11: Isochore maps for the Mozambique Basin. (a) MBSU-1 (b) MBSU-2 (c) MBSU-3 (d) MBSU-4 (e) MBSU-5 (f) MBSU-6. The gravity anomaly marking the Beira High is indicated by a black outline. Note that the sediment thickness above Beira High is almost negligible for MBSU-1 to MBSU-3 because of its elevated topography. MBSU-5 shows a rapid deposition of sediments in the Zambezi Delta coinciding with the start of onshore tectonic activity; with permission from Elsevier

prominent valleys also incise the seafloor across profile BGR07-204 in the SW-NE direction (Figure 4.7, SP 1140-1210 and 1580-1750). The valleys have sedimentary infills with contrasting reflector patterns. The valley at SPs 1580-1750 has steep sides and a fill of continuous parallel reflectors, while the other channel is relatively narrow with parallel reflectors underlain by obliquely aggrading chaotic-hummocky reflectors. A channel-levee complex dominates the sedimentary pile on Beira High. The channel is filled with relatively young sediments defined by strong parallel reflectors that onlap the flanks of the channel. Between the shelf and Beira High several buried channels are observed at the interface of MBSU-4 and MBSU-5.

4.5. Discussion

4.5.1. Early development and basement structure

The basement in the Northern Mozambique Basin is composed of a thick oceanic crust with a continent-ocean transition zone located close to the coast as interpreted from P-wave modelling (Leinweber et al., 2013). The depth to basement in the ZDD might be greater than shown because of the low resolution of the deepest reflectors. To the south of ZDD, lava flows and end-rift volcanics are interpreted (Mahanjane, 2012; Nairn et al., 1991; Salazar et al., 2013; Salman and Abdula, 1995). A similar depth to basement is observed on the conjugate margin in the Riiser-Larsen Sea between Astrid Ridge and

Gunnerus Ridge (8-10 km) (Figure 4.4 in Leitchenkov et al., 2008) and on the adjacent margin in the Somali Basin 7-11 km) (Figure 4.15 in Coffin, 1986).

The thickness of sediment cover ranges from 10 km in the ZDD to 4 km in the deepest parts of the surveyed area. Due to uncertainties of deeper sediment velocities and limitations of the interpolation algorithms near the edges of the data set, the extreme values in the ZDD should be ignored. With this exception, the range of sediment thickness (4-9 km) is marginally greater than that reported in the Somali Basin (4-8 km; Fig 14 in Coffin et al., 1986) and Riiser-Larsen Sea (3-7 km; Fig 20 in Leitchenkov et al., 2008).

Figure 12 shows the comparison of sedimentation rates at different locations within the basin and values calculated from wells near our study area. The sediment thicknesses are not compensated for compaction, therefore, we interpret only the trend for older sediments at each location that are buried at significant depths where the compaction factor would be comparable.

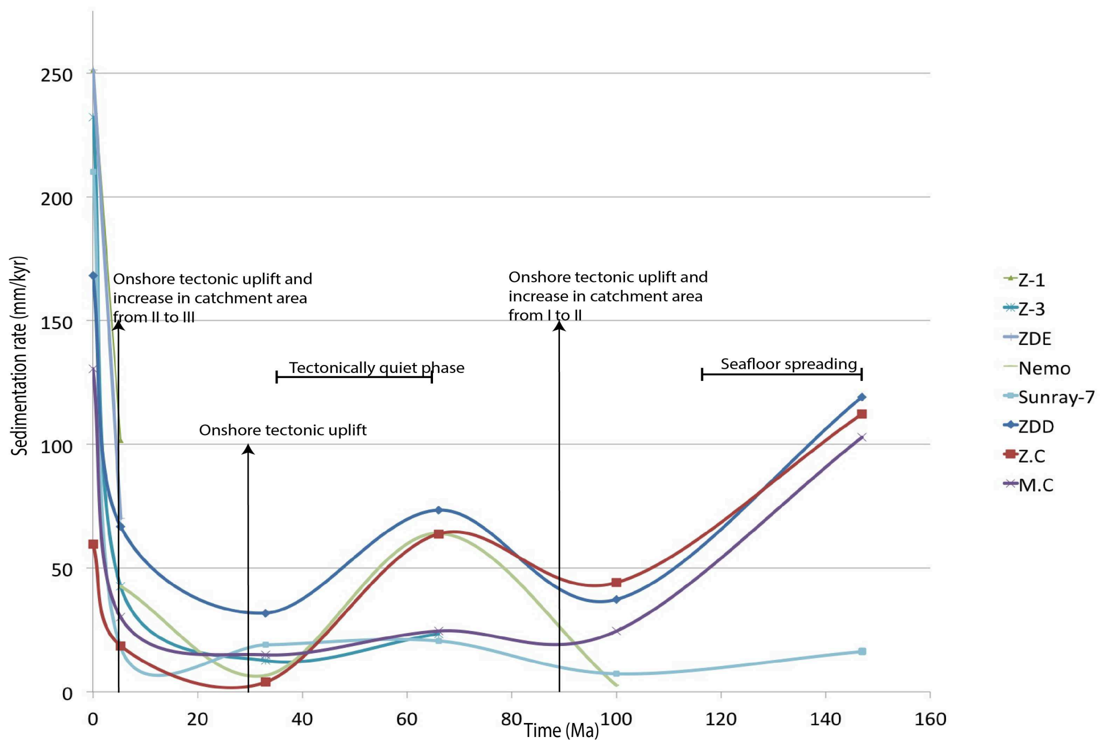


Figure 4.12: Sedimentation rate computed (not compensated for compaction) at different locations (see fig 1 for location) using well data and seismic data. Abbr. Z-1 Zambezi-1 well, Z-3 Zambezi-3 Well, ZDD Zambezi Depression Delta, Z.C. Zambezi channel, M.C. Mozambique Channel; with permission from Elsevier.

The initial rifting process that separated East and West Gondwana resulted in the deposition of thick Jurassic sediments into a young basin. A decrease in the sedimentation rate from 10cm/kyr in Jurassic to 4 cm/kyr in Early Cretaceous can be seen. The sediment volume needs to be compensated for the continuous growth of the oceanic Mozambique Basin. The sedimentation rates increase to 6 cm/kyr during Late Cretaceous times. It might be up to 8cm/kyr if we consider that most of the sediments were deposited after 90 Ma. A drop in Early Cenozoic sedimentation rate to 2.5 cm/kyr is observed. No major tectonic activity is observed on the African continent during this phase. Patridge and Maud (1987) suggest the advanced stages of planation of the African surface supplied minimal sediments to the African rivers and, thus, explains minor sediment discharge into the basin.

4.5.2. Jurassic and Early Cretaceous

Beira High plays a key role in controlling the sediment deposition in the ZDD. From the isochore maps of MBSU-1 (Figure 4.11a) we can see that most of the initial sediment influx from the Zambezi was trapped in the depression between Beira High and the continental margin. Jurassic sediments appear as infill between faulted and rotated blocks on the outer Beira High. Very little or no Jurassic sediments are observed on Beira High, presumably because the elevated topography did not permit any significant deposition. The sediment units on the outer Beira High are also rotated by different angles, supporting the interpretation of Mahanjane (2012) that these are syn-rift sediments deposited contemporaneously during the second break-up phase of Gondwana (Mahanjane, 2012; Reeves, 2000). Jurassic and Early Cretaceous sediments are interpreted to have been transported to their marine depocentre by East African rivers during the development of the Mozambique Basin. Jurassic sediments appear mostly as draping the oceanic basement. These reflectors are divergent with a very steep gradient (2-6°) in the continent-ocean transition zone and sub-parallel in the basin, indicating significant ongoing subsidence till the Late Cretaceous (Figure 4.4b). A simple back-of-the-envelope calculation shows basement subsidence of more than 4 km during this period. The cause for the low velocity layer in MBSU-2 is difficult to determine without well data. However, well data from Nemo -1 and Sunray 7-1 establish the presence of black shales that were deposited under euxinic conditions (De Buyl and Flores, 1986). The seismic velocity trend observed here is similar to that used in oil exploration to identify undercompacted, overpressured shale (Upadhyay, 2004). Rift basins support the deposition of salt, evaporites or the build up of carbonate bodies. In contrast to the Rovuma Basin, where salt domes penetrate Jurassic reef massifs (Salman and Abdula, 1995), neither salt tectonics nor reef massifs are observed in any of the profiles presented here.

4.5.3. Late Cretaceous

Deformation of the basement and the overlying Mesozoic sediments interpreted in profiles BGR07-203 and 204 suggests that a tectonic event led to isolated deformation of the Mozambique Basin in Late Cretaceous or later times.

Across the Mozambique Channel, basalt flows in the northern part of Madagascar's Morondava Basin, considered related to Marion hot spot, are interbedded with Upper Cretaceous sedimentary rocks all along the 1500-kilometer-long rifted eastern margin of Madagascar, which formed by the opening of the Mascarene Basin (Storey et al., 1995).

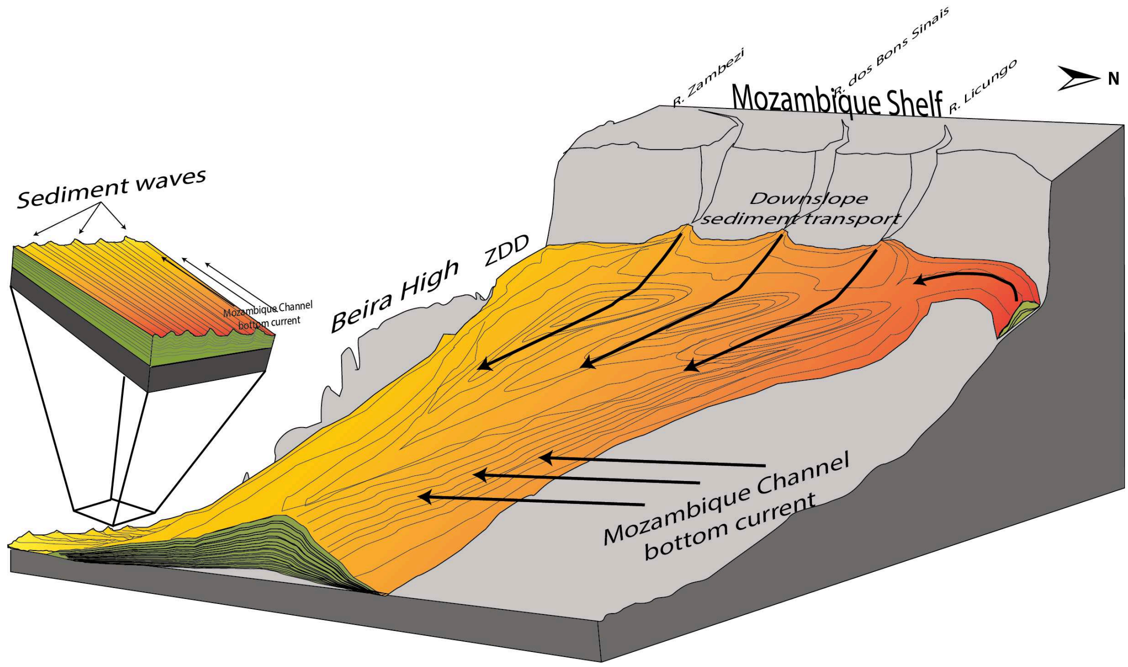


Figure 4.13: Schematic sketch of the Late Cretaceous Mozambique Fan. The fan is located between the mouths of the present-day Zambezi and Licungo rivers. Sediments from the Mozambique Fan were transported eastwards around the northern edge of Beira High before being deflected southwards by a bottom current. This resulted in a steeper gradient on the northern flank than in the south. Sediment deposition is controlled by the north-south bottom current resulting in sediment wave structures to the east of Beira High within the channel as seen in BGR07-207 (Figure 4.9); with permission from Elsevier.

^{40}Ar–^{39}Ar and U-Pb zircon age determinations reveal that these volcanic rocks and dikes were emplaced rapidly, with a mean age of 87.6 ± 0.6 Ma. Therefore, we can interpret the basement deformation in the Mozambique Basin as a far-field expression of the same Late Cretaceous stress field in which the Mascarene Basin initiated. However, the exact nature of the deformation cannot be identified in the absence of a 3D or deeper seismic survey.

A thick layer of sediments in the Zambezi delta (Figure 4.11c) and its prograding shelf mark the increased sediment influx of the Zambezi River that can be attributed to rapid denudation of southern Africa in the Late Cretaceous (Patridge & Maud, 1987; Walford et al, 2005). The epeirogenic uplift of the African continent post Early Cretaceous around the time Kimberlite emplacement 90 Ma (Patridge and Maud, 1987 and references therin) undoubtedly generated a high topography that was subjected to heavy erosion. The wedge-shaped structures observed in the profile BGR07-201 (Figure 4.4), BGR07-202 (Figure 4.5) and BGR07-204 (Figure 4.7) are interpreted as an elongated submarine fan lobe of the Zambezi delta that flowed into the channel around the northern edge of Beira High eventually turning to the south (Fig 13). It should be noted that the depocentre of the Mesozoic Zambezi is located to the north of the present-day mouth of the river. It moved southwards in Cenozoic times. This is corroborated by the isochore maps of Walford et al. (2005)(their figure 7). Unlike typical submarine fans, no indenting canyons or channels can be observed. The proximal fan has an ellipsoidal shape whereas the distal fan is more triangular. The main lobe has a steep northern flank and, over time, the depocentre continuously shifts towards the south (Figures 4.4, 4.5). This indicates the influence of two currents on the deposition of the sediments. First, a strong turbidity current originating from the shelf transported sediments into the channel in the west-east direction. The influence of the turbidity current wanes with increasing distance from the shelf and a north-south bottom current started to dominate in the distal fan lobe, confining the sediment deposition on the southern flank. Therefore, the morphology of the sediment body is a product of at least two current systems. Smaller sediment wedges on the continental rise seen in profiles BGR-202 and BGR07-203 are interpreted as contourites because of their internal reflection patterns. They were probably deposited by the north-south current, whose onset can thus be dated to Late Cretaceous times. The notional onset of a north-south current in Late Cretaceous times is corroborated by the sediment wave structures observed within MBSU-3 in profile

BGR07-207 (Figure 4.10). Sediment waves are associated with current-controlled drift bodies (Rebesco et al, 2014).

In the deeper basin, the reflector gradient ascends away from Beira High, implying the influence of a northeastern sediment source. We presume this to be an extension of the southwestern flank of the fan lobe from the north. Coffin et al. (1986) also suggest the start of a north-south bottom current from the observed contourites deposition in the Somali basin in Late Cretaceous. This suggests a shore-parallel current that originated in or north of the Somali Basin that flowed into and through the Mozambique Channel in Late Cretaceous times.

4.5.4. Early Cenozoic

The onshore quiet tectonic phase described by Burke (1996) is also reflected in the sedimentation rate within the basin. No major features are observed within the basin during this phase. It culminates with a prominent erosional unconformity of a sediment-starved basin during mid-Oligocene marine regression. The data presented here show no observable trend of sediment transport during this phase except for a few minor valleys indenting the sediment unit above Beira High. The strong bottom current through the channel appears to wane during this period as no major current controlled features are observed. It may have ceased or moved further east, closer to the Davie Ridge. Droz and Mougenot (1987) show that the southward flowing Serpa-Pinto valley was the main sources of sediment supply to the deep sea Upper Mozambique Fan from the Oligocene to early Miocene.

4.6. Conclusion

This study introduces a regional stratigraphic framework for the Mozambique Basin. The oceanic basement of the Mozambique Basin subsided rapidly until Cretaceous times. Rough estimates indicate that it might have subsided by more than 4 km during Mesozoic. The timing and amount of subsidence are consistent with what might be expected from normal thermal subsidence of Jurassic oceanic crust. Until the Early Cretaceous, we interpret restricted oceanic circulation within the basin resulting in occasional euxinic conditions and continuous aggradation of fluvial sediments. Major tectonic events along the East African margin are reflected in the Mozambique Basin. The sedimentation rate in the basin is strongly influenced by the onshore tectonic activity. Surge in sediment influx is preceded by episodes of tectonic uplift of the African continent. However, evidence for tectonic activity affecting the oceanic crustal basement is very limited within the research area.

The environmental setting of the Mozambique Basin changed from a restricted and potentially-euxinic basin in Early Cretaceous times to a current-swept basin in Late Cretaceous times, with the onset of a north-south bottom current in the Mozambique Channel. The bottom current is observed along the east African margin and originated from or further north of the Somali Basin. The surge in sediment influx in Late Cretaceous times and the onset of this north-south bottom current resulted in the formation of a peculiar elongated submarine fan on the continental rise. This Late Cretaceous Mozambique Fan was most likely the main conduit for sediment influx into the Mozambique Channel. The submarine fan was active until Early Cenozoic when it was starved of sediment resulting from reduced transport by the Zambezi River. The effect of the north-south bottom current waned during the Cenozoic and eventually ceased or confined to the deeper basin within the channel.

4.7. Acknowledgements

We gratefully acknowledge the contributions of Dieter Franke and Graeme Eagles for their effort in improving the manuscript in terms of content and English. We also thank the French polar institute (IPEV) for the logistic and financial support and the captain and crew of Marion Dufresne II (IPEV) for their excellent work during the expedition. All maps were created using GMT 5.0 (Wessel et al., 2013).

Chapter 5: Anomalous bathymetry and palaeobathymetric models of the Mozambique Basin and Riiser Larsen Sea

Authors:

Jude A. Castelino , Graeme Eagles, Wilfried Jokat

Alfred Wegener Institute, Hemholtz Centre for Polar und Marine Research (AWI), Am Alten Hafen 26, D-27568, Bremerhaven, Germany

Earth and Planetary Science Letters

Submitted: 04 April 2016

Status: minor revisions (19 June, 2016)

Keywords

Palaeobathymetry, African Uplift, backstripping, Mozambique Channel, Late Cretaceous bottom current, dynamic topography.

5.1 Abstract

In this study we introduce a palaeobathymetric model for the conjugate Mozambique Basin and Riiser-Larsen Sea built by employing backstripping techniques, compensating for dynamic topography and plate motions. The model is presented at 0.2° x 0.2° grid resolution, making it suitable for future oceanographic and climate simulation model experiments aimed at a better understanding of the climatic and oceanographic relevance of oceanic gateways in the southern ocean. At the present day, the seafloor next to the Mozambican continental margin is around 300 m shallower, and that in the central Mozambique Channel is almost 1300 m shallower, than their conjugate areas or the predictions of oceanic thermal subsidence models. The cause of this anomalous depth is difficult to determine confidently because of sparse data, in particular concerning sediment thickness, and because of the wide range of amplitudes in modelled present-day dynamic topography. The distribution of shallow seafloor suggests that it might be attributed to the presence of thicker-than-usual oceanic crust, which in turn can be attributed to the Paleogene passage of the Quathlamba plume beneath the basin. We portray these effects in our palaeobathymetric models. In contrast, the Riiser-Larsen Sea has experienced fairly stable subsidence since its formation in Jurassic times, with only slight observable changes attributable to the onset of Antarctic glaciation and during the middle Miocene climate transition. Both basins display flexure over half-wavelengths of ~60-80 km with amplitudes of 1500 m towards their continental margins. This plays an important role in models of palaeobathymetry for times older than 100 Ma. Near the margins, isolated areas of transitional or debatable crustal composition, including Beira High and Gunnerus Ridge, are depicted to subside in a similar fashion to oceanic crust. Further into the Indian Ocean, oceanic lithosphere younger than 100 Ma on both plates has subsided to depths that are typical of thermal subsidence models. Finally, the new palaeo-bathymetry had distinct consequences for the current systems in the young Southern Ocean during the time periods. The onset of coast-parallel bottom currents and associated contourite deposition in the Mozambique Channel at palaeo water depths of 3500-4000 m may be a consequence of either an opening of a deep-water passage into the South Atlantic between Southwest Indian Ridge and Agulhas plateau or into the Tethys Ocean in the Late Cretaceous.

5.2 Introduction

Palaeobathymetric models are essential for quantitative testing of palaeo-climate hypotheses, and as constraints on models of regional sediment transport and deposition and the linkages between tectonics and surface processes. This was recognized as early as the 1970s with subsidence studies in sedimentary basins (Steckler and Watts, 1978; Watts and Ryan, 1976). Since then, a variety of parameters that influence the evolution of basin depth have been identified, and techniques for modelling being refined, to create improved models. Recent, detailed palaeo-bathymetric studies in the Northern Atlantic Ocean and Weddell Sea show the significance of such improved models for the polar regions to improve numerical circulation models and increase confidence in their interpretation (Ehlers and Jokat, 2013; Huang et al., 2014; Wold, 1995).

Here, we describe a palaeobathymetric modelling study for the African-Antarctic corridor, with a focus on its extremities, the Riiser Larsen Sea and Mozambique Basin (Figure 5.1). The basins and the corridor are of interest palaeo-climatically, because of suggestions that early stage excess volcanism in them led to the formation of oceanic plateaux that restricted vertical mixing and water exchange, leading periodically to large-scale eutrophication. This possibility has been linked as a possible cause to one or more of several anoxic events that occurred during the Jurassic and Cretaceous (Burgess et al., 2015; Turgeon and Creaser, 2008). Rigorous tests of this or related suggestions with climate and oceanographic circulation models will require high-resolution palaeobathymetric reconstructions of the region for this time period. Such models are now possible for the corridor thanks to the collection of extensive seismic (Figure 5.1) and magnetic datasets in recent years (Castelino et al., 2015; König and Jokat, 2006; Leinweber et al., 2013; Leitchenkov et al., 2008) that have yielded new and detailed information on stratigraphy, the age of the oceanic crust, and the location of the continent-ocean transition zone.

5.2.1 Geological constraints on palaeobathymetry: Plate Kinematics and regional vertical motions

The break-up of Gondwana started with the separation of East Gondwana (comprising Antarctica, Madagascar, India, and Australia) from West Gondwana (comprising Africa and South America) during the Early Jurassic. In the study area, this breakup led to

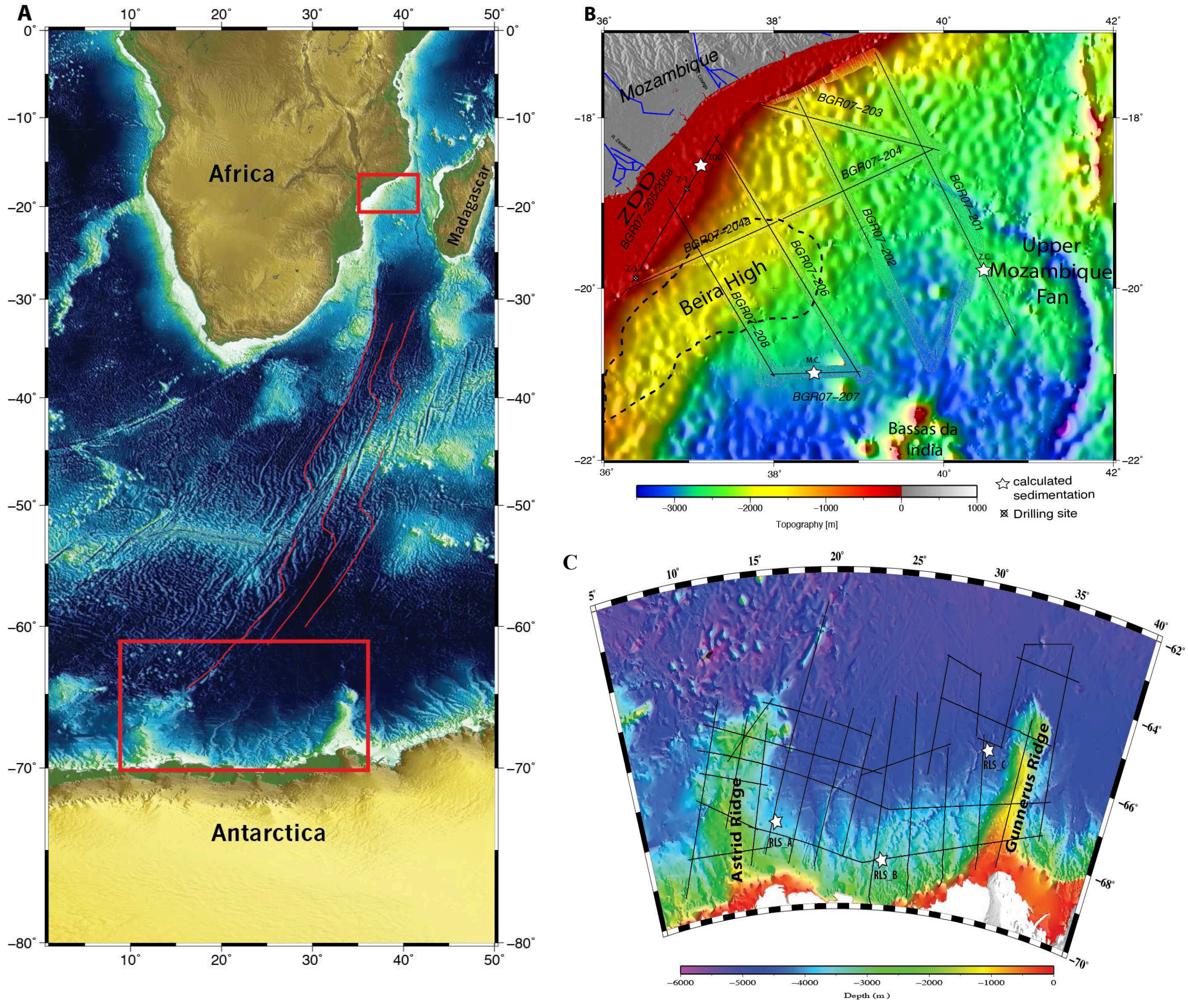


Figure 5.1:(A) Bathymetric map of Africa –Antarctic corridor. The red flow lines indicate the Southwest Indian ridge motion between Africa and Antarctica. Red boxes indicate the study area of the reconstructed palaeobathymetry. Bathymetry map of the (B) Mozambique Basin and (C) Riiser-Larsen Sea. The outline of Beira High (dashed line) is interpreted from gravity anomaly. Gunnerus and Astrid ridges are identified by their shallow topography. The seismic lines used in this study are indicated with black lines.

formation of the present-day East African passive margins and their Antarctic conjugates, and the Riiser Larsen Sea and Mozambique basins. The initial phase of separation was characterized by rifting and the emplacement of Karoo-Ferrar flood basalts during massive volcanism in Africa and Antarctica, with peak activity occurring between 178 and 184 Ma (Burgess et al., 2015; Eagles and König, 2008; König and Jokat, 2006). The oldest identified magnetic anomaly is M42 in the Somali and Mozambique Basins, implying seafloor spreading was underway at approximately 167 Ma (Gaina et al., 2015; Leinweber and Jokat, 2012). Several plate kinematic models exist that aim to describe the separation of the plates along the entire East African Margin (e.g. Gaina et al., 2013; Leinweber and Jokat, 2012; Eagles and König, 2008).

The initial movements within Gondwana during this period are poorly constrained, although Eagles and König (2008) suggest that the orientation of plate motion is likely to have remained constant through the breakup phase on the basis of the parallelism of fracture zone and onshore fault trends in Tanzania. After this, in two phases of breakup, Antarctica moved first to the SSE relative to Africa as part of East Gondwana, leading to opening of the oldest basins off Mozambique and Somalia, and later moved southwards accompanying the disintegration of East Gondwana.

Because of its thick ice cover, little information is available on the tectonic and erosional history of Dronning Maud Land, Antarctica to enable detailed interpretation of its vertical motions since the Jurassic. In contrast, for the African plate, multiple lines of evidence suggest pulsed Miocene, Pliocene and ongoing uplift, by in total as much as 2.4 km, of continental South Africa in response to the transmission of viscous stresses from upwelling mantle rocks to the lithosphere (Burke, 1996; Gurnis et al., 2000; Partridge and Maud, 1987; Roberts and White, 2010). Prior to this time period, a more modest uplift is suggested to have followed a quiet tectonic period between 65 and 30 Ma, perhaps related to a previous pulse or phase of mantle upwelling (Partridge and Maud, 1987). Whether the present-day landscape of Africa expresses the effects of even earlier uplift events, and what their causes may have been, is a complex and fiercely debated topic (Roberts and White, 2010 and references therin). Across the Mozambique Channel, Roberts et al.'s, (2012) analyses of the shapes of river profiles allow them to estimate that the last 15 Myrs have seen uplift of Madagascar by 1-2 km, which they attribute to sub-lithospheric mantle convection.

5.2.2 Geological constraints on palaeobathymetry: Anomalous crustal blocks

Our study area hosts several bathymetric and basement highs whose crustal affinity is debatable. The Gunnerus Ridge (Figure 5.1) is aligned approximately along 34ºE longitude at the East Antarctic continental margin with an E-W width of about 100 km, and extends 450 km northwards into the Southern Ocean. It forms the eastern border of the Riiser Larsen Sea and has an average elevation of 2500 m relative to the adjacent seafloor. Leitchenkov et al. (2008) interpreted the ridge as a continental fragment with a crustal thickness of 25-27 km.

The Astrid Ridge (Figure 5.1) lies off the Princess Astrid Coast section (5°E to 20°E) of East Antarctica, rising to ~1000 m above the surrounding seafloor. Dense aeromagnetic data over this seafloor reveal Jurassic magnetic seafloor anomalies representing the oldest age constraint for the breakup of Gondwana (Leinweber and Jokat, 2012). The topography and shape of the southern part of the ridge suggest it formed as a consequence of massive volcanic activity during this early phase of seafloor spreading (Leitchenkov et al., 2008). The Mozambique Ridge, lying in the corridor of oceanic lithosphere formed adjacent to that occupied by Astrid Ridge, is also interpreted to be a result of excess volcanism (König and Jokat, 2010). The northern edge of Astrid Ridge and the sharp eastern margin of the Mozambique Ridge on the African plate probably both record the cessation of excess volcanism near the end of the Cretaceous normal polarity interval. Thus, the southern part of the ridge might at least have erupted between 140 and 122 Ma. A continuous pair of fracture zones confines the eastern and western limits of the two features.

The Beira High (Figure 5.1) is a buried basement high off the Zambezi Delta. The exact composition of the crust is not yet determined. Here, by analogy to the features described above, we consider it may either be a relic of the African continental crust separated during initial breakup phase or a later result of excess magmatism.

5.3 Aims, objectives and methods

Given the data and constraints outlined above, we designed a palaeobathymetric modelling study to address the following questions:

- How did seafloor topography evolve over the time since the separation of the conjugate margins?
- Have the two marginal basins evolved according to predictions of thermal subsidence models for oceanic crust?
- What, if any, influence did Late Cretaceous and Cenozoic uplift of the African continent have on subsidence in the basins?
- How did the Beira High, Gunnerus and Astrid ridges reach their present depths?
- Have the basins been affected by tectonic processes after their formation by seafloor spreading?

The objective of the study is thus to model palaeobathymetry in a two-step method that involves (1) estimating the depth of the seafloor at a given point in time using the principle of backstripping, and (2) using plate kinematic models to restore the plates bearing the seafloor to their relative positions at past times.

5.3.1 Backstripping of sediment layers

Backstripping is a method to reconstruct palaeo-seafloor depth by removing sediment layers belonging to units that post-date the age of the reconstruction. The resulting topography is compensated for the effects of sediment compaction and isostatic balance owing to the removed sediment load, as well as for eustatic sea-level variations. In our study area, there is no evidence for salt tectonics or major faults that disrupt the stratigraphic sequence (Castelino et al., 2015; Leitchenkov et al., 2008). Therefore, the backstripping technique alone should be sufficient to estimate past seafloor topography with no requirement for palinspastic modelling.

Palaeobathymetry is calculated on sample points with a regular spacing of 0.2º x 0.2º in the Mozambique Basin and in the Riiser Larsen Sea using a C program routine, BalPal v0.9, scripted by Wold (1995), with modifications by Ehlers and Jokat (2013) and for this study. Unlike previous studies, which used 1º x 1º grid cells, the closer spacing of our calculation points justifies continuous interpolation at high resolution. The following text describes the parameters used in this study.

5.3.1.1 Stratigraphy and lithology

The stratigraphy for each grid cell is derived from the seismic interpretations of Castelino et al. (2015) in the Mozambique Basin and Leitchenkov et al. (2008) in the Riiser Larsen Sea**.** Their regional seismic networks extend from the shelf edge into the deeper abyssal basins. The seismic sections are converted from Two-Way-Travel (TWT) time to depth using seismic Normal move-out (NMO) velocity models. The NMO velocity models are quality controlled by wide-angle seismic and sonobuoy data. There are no well data to provide a lithostratigraphic framework for the Riiser-Larsen Sea. Instead, the stratigraphic horizons are correlated to their basement onlap and assigned similar ages as the oceanic crust, as determined from magnetic isochrons (Leitchenkov et al., 2008).

Compaction of sediments is related to its porosity and lithology. Due to the absence of *in-situ* porosity information from the wells, we have to rely on best fitting global estimates. We chose to use the exponential functions of Bahr et al. (2001), whose study convincingly compares empirical and numerical approaches to understanding compaction processes.

5.3.1.2 Thermal subsidence and age of the lithosphere

For the calculation of thermal subsidence of the lithosphere, we equate the thermal age to the crustal age based on identified magnetic anomalies in the Mozambique Basin (Leinweber and Jokat, 2012) or rifting or eruption age for anomalous crustal blocks. We use this information to create a regional age grid based on the geological time scale of Gradstein et al. (2012). In the Riiser-Larsen Sea, we modify the global age grid compilation of (Müller et al., 2008a) (Figure 5.2). The thermal subsidence is calculated using the age-depth relation in the Global Depth and Heat flow (GDH1) model of Stein and Stein, (1992). The model assumes a square-root function for thermal subsidence for oceanic lithosphere younger than 20 Ma:

$$z = 2600 + 365\mathrm{sqrt}(t)$$

where t is the age of the crust and z is the basement depth

and an exponential function for the observed depths of older oceanic lithosphere:

$$z = 5651 - 2473\exp(-0.0278t)$$

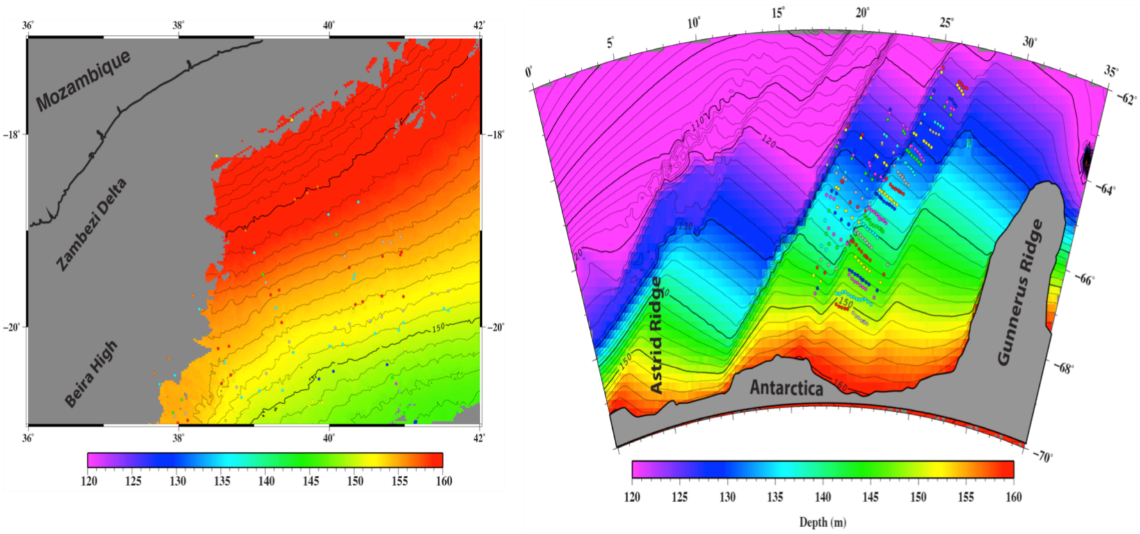


Figure 5.2: Age grid model of (A) Mozambique Basin and (B) Riiser-Larsen Sea (Müller et al., 2008a). The age model in the Mozambique Basin is derived from magnetic anomalies identified by König and Jokat (2006) and Leinweber and Jokat (2012). The age model of Müller et al., (2008) is modified using magnetic anomalies identified by König and Jokat, (2006) (coloured circles) . Time scale for both regions is based on Gradstein et al. (2012).

GDH1 is thought to be applicable only to oceanic lithosphere that has formed by steady cooling of mantle material brought close to the seafloor by plate divergence. In reality, seafloor depth also evolves in response to large changes in the composition, temperature, and flow direction of sub-lithospheric mantle, all of which can be related to its convection, and to the development of oceanic plateaus and seamounts by excess volcanism. Large deviations from thermal subsidence models like GDH1 can be interpreted in terms of either of these processes, as we will discuss later.

5.3.1.3 Eustatic sea-level curve

The modelled seafloor topography is displayed with reference to its palaeo-sea level. In the absence of any regional information from either margin, we use the global eustatic sea level curve of Haq and Al-Qahtani (2005) as a basis for applying eustatic corrections in the backstripping analysis.

5.3.1.4 Isostatic Balance

We assume Airy isostasy in order to compensate for the reduced load on the crust due to removal of sediments and changing sea-level during backstripping. The compensation depth is set to 100 km and maximum asthenosphere density is set to 3400 kg/m^3. Based on seismic refraction modelling, Leinweber et al., (2013) and Mueller et al., (in prep) report an average density of 2800 kg/m^3 for the 7-9 km thick oceanic crust in the Mozambique Basin. (Leitchenkov et al. (2008) show that the crustal properties are similar in the Riiser Larsen Sea with an average density of 2800 kg/m^3 and average thickness of 7-10 km. Because of this, we use a constant density of 2800 kg/m^3 and constant oceanic crustal thickness of 7 km in both basins. The continental crust on both margins and below Gunnerus Ridge is up to 30 km thick (Leinweber et al., 2013; Leitchenkov et al., 2008; Mueller et al., in prep). Sediment densities are computed for each lithology based on the porosity-depth function of Bahr et al. (2001).

5.3.2 Plate rotation parameters

For this study, plate rotation parameters are taken from Leinweber and Jokat, (2012) for times prior to 100 Ma and (Eagles and König, 2008) for later times. We focus primarily on the palaeo-positions of African, Antarctic and Madagascar plates with respect to each other since 140 Ma. Owing to their peripheral role, we omit or simplify detailed kinematics in regions neighbouring our model, for example involving India, Sri Lanka, Maurice Ewing Bank and the Falkland Plateau.

5.3.3 Supplementary data in African-Antarctic Corridor (AAC)

In addition to our focus on the Mozambique Basin and Riiser Larsen Sea, we also show Mesozoic palaeobathymetry modelled for the intervening Africa-Antarctic corridor. The input data for this are primarily derived from the GEBCO bathymetry grid. In addition, we make the following assumptions:

- Negligible sediment cover over the Mozambique Ridge, Agulhas Plateau Madagascar Plateau and Maud Rise.
- The thermal evolution of large igneous provinces (LIP) and oceanic plateaus and its influence on their subsidence are poorly understood. Since such features mostly show a 20-25 km crust including the neighbouring Agulhas Plateau (Gohl and Uenzelmann-Neben, 2001; Mueller et al., 2016), for simplicity, we use a subsidence curve parallel to that of the GDH1 model built with an assumption of 20 km oceanic crust with density 3000 kg/m^3.
- Seismic data around 28° S in the Mozambique Channel, where the lithosphere formed at ~100 Ma, reveal a sediment thickness of ~1000 m (Reichert, 2007). Therefore, in our calculations, the sediment thickness varies from 0 to 1000 m over oceanic crust aged between 0 and 100 Ma (~28° S), and in the range 1000-3000 m for 100-140 Ma aged lithosphere in the Mozambique Channel. Sediment thickness varies in the range 0-1000 m for 0-120 Ma crust on the Antarctic plate.
- In the absence of any lithostratigraphic information we assume a constant sedimentation rate for backstripping.

5.4 Results and discussions

In this section we describe the some *ad hoc* modifications to palaeobathymetric maps produced using BalPal, and discuss the processes that might have given rise to the need for them.

5.4.1 Modifications for anomalous bathymetry of the Mozambique Basin.

Figure 5.3 shows the results of a reconstruction of sea floor topography at 140 Ma, made taking into account the expected contributions of sedimentation and thermal subsidence as described above. It is immediately obvious that the seafloor of the Mozambique Basin is much shallower than its conjugate Riiser-Larsen Sea. That this should be unreasonable is particularly illustrated by the sharp step at the modelled palaeo-ridge crest, at which no large height difference should exist. Figure 5.4 shows that this imbalance comes about because the sediment-stripped basement depth of the Mozambique Basin for present-day is as much as 1300 m or more shallower than GDH1 or any other thermal subsidence model predicts seafloor of its age should be.

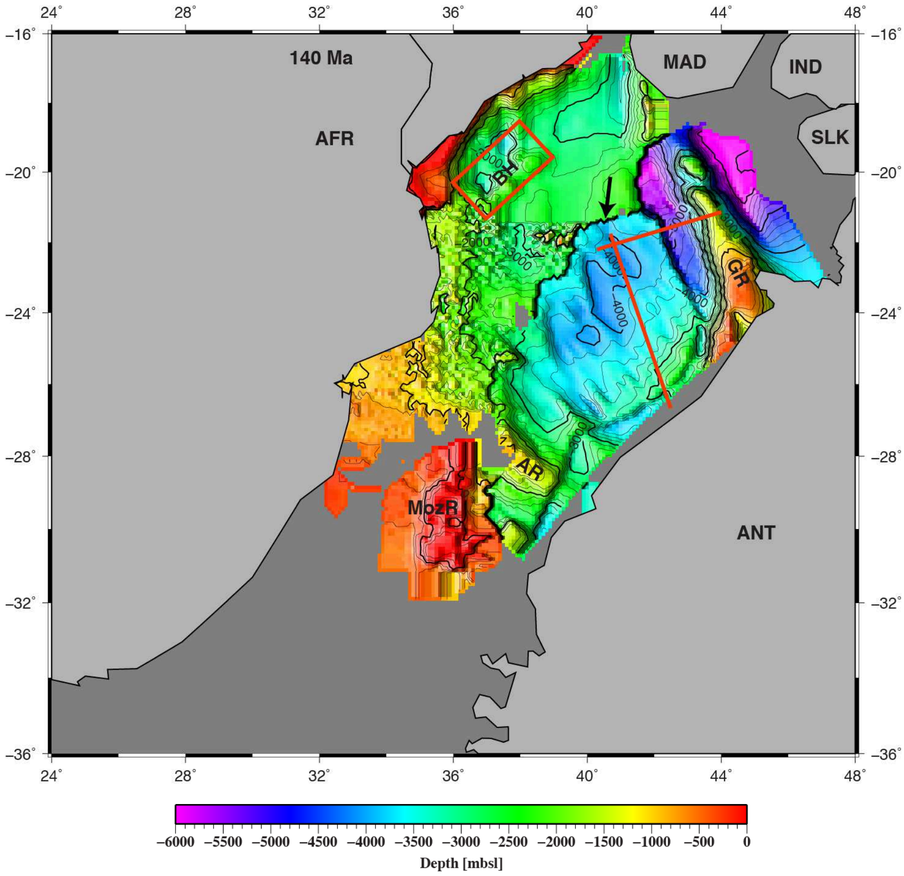


Figure 5.3: Results of palaeobathymetry reconstruction with Beira High as continental crust and without dynamic topography. The Mozambique Basin is shallower than Riiser-Larsen Sea by at least 1300 m at the ridge crest (black arrow). Modelled Beira High is at least 600 m deeper than the surrounding seafloor at 140 Ma. A short wavelength topography can be observed at the COTZ along the Antarctic margin and Gunnerus Ridge (solid red lines indicate location of profiles illustrated in Figure 5.8) Abbr: AFR= African Plate; ANT= East Antarctic Plate; MAD=Madagascar; IND= Indian Plate; SLK= Sri Lankan Plate; BH= Beira High; MB= Mozambique Basin; RLS= Riiser-Larsen Sea; GR= Gunnerus Ridge; AR= Astrid Ridge

In comparison, within scatter, GDH1 is consistent with unloaded basement depth everywhere on the Antarctic side of the SW Indian Ridge except close to the continental margin, and in 50-100 Ma-aged seafloor on the African plate. The inset map shows that the anomalous residual bathymetry in pre-100 Ma African plate seafloor is a feature of the entire Central and Southern Mozambique basins. The asymmetry attests to some process that has altered the usual pattern of thermal subsidence of a large area to cause an uplift of parts of the African Plate only. From this observation, we can rule out processes at the active divergent plate boundary when the basins formed. In the following, we discuss other possible explanations for the anomaly.

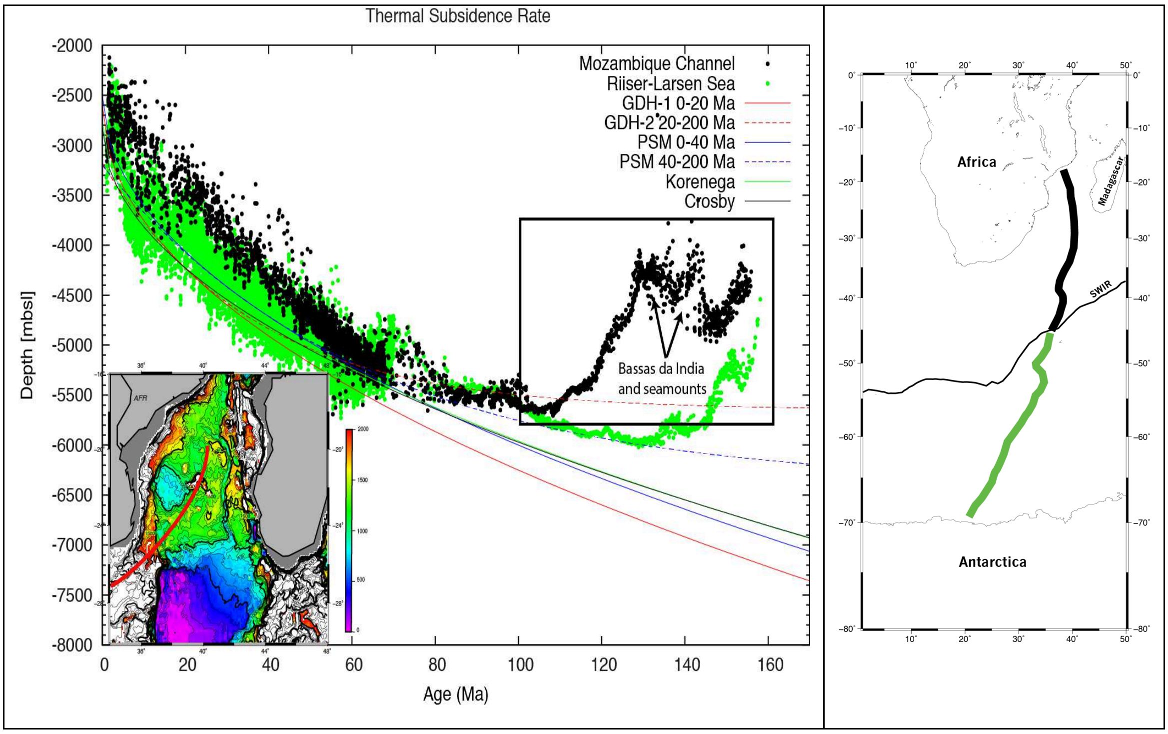


Figure 5.4: Age vs Depth relationship for thermal subsidence of oceanic crust (GDH1= Stein and Stein 1992; PSM = Parsons and Sclater, 1977; Korenega = Korenega and Korenega, 2008; Crosby = Crosby et al, 2008). GDH1 and PSM model assume a flattened curve for oceanic crust older than 70 Ma whereas other models assumed anomalous lithosphere. The basement depth vs age along a transect derived from global bathymetry (GEBCO) stripped of sediments estimated from Castelino et al (2015) in the Mozambique Basin and Whittaker et al. (2013) elsewhere show a good correlation with GDH1 till 100 Ma. Inset map shows the residual bathymetry of the Mozambique Basin and the Quathlamba hotspot trail (Almirante Leite - Bassas da India volcanic lineament) in red.

Dynamic Topography

Earlier, we noted that multiple studies have concluded the occurrence of km-scale uplift of South Africa and Madagascar in Neogene to present times. There is consensus that these uplifts are examples of dynamic topography, a consequence of the transmission of viscous stress from upwelling mantle rocks to the base of the lithosphere. Given its location and its amplitude, the anomalous bathymetry of the Mozambique Basin forms a natural link between these two regions, suggesting it may be reasonable to view it too as a consequence of dynamic topography at the present day. Dynamic topography can be estimated by assuming global seismic tomographic models provide a snapshot of mantle convection, from which the transmission of viscous stress can be estimated after assuming a mantle viscosity profile. The uncertainties, however, are large; modelled amplitudes for the present-day Mozambique Basin differ between values that are comparable to the depth anomaly in Figure 5.3 (Gurnis et al., 2000) and values that are an order of magnitude smaller (Müller et al, 2008b). The wavelengths of topography in all of these models are far longer than the sharp southern edge of the bathymetric anomaly at ~26°S in the Mozambique Channel, suggesting either that tomographic imaging fails to capture details of mantle upwelling that has real topographic consequences at the surface, or that the anomalous bathymetry of the Mozambique Basin has other or further causes.

Crustal Thickening

Models like GDH1 are generated only by considering cooling of the mantle by thermal conduction and assume, almost implicitly, that the lithosphere is topped by a constant-thickness crust. The assumption is adhered to in the choice of input bathymetric data to which the models are tuned. Because of its lower density than mantle rocks, the top surface of a thicker than usual igneous crust will lie at a shallower depth than that of regular oceanic crust. Generating such a thick crust requires a supply of excess melt from the mantle. Storey et al. (1995) and Torsvik et al. (1998) report the onset of emplacement of volcanic rocks related to the Marion hotspot in the Morondova Basin, adjacent to the Mozambique Basin, at ca. 91 Ma. Castelino et al., (2015) identified disturbed basement most likely caused by changes in the Late Cretaceous stress field in the central Mozambique Basin, consistent with the possibility that mantle material related to this hotspot may have suffused westwards to act as a source of melt in mid Cretaceous times. Alternatively, (Hartnady, 1985) hypothesized the so-called Quathlamba hotspot to explain the production of the Almirante Leite – Bassas da India volcanic lineament that crosses the Central Mozambique Basin (19.92°N 39.94°S) towards a region of thin crust with high heat flow with modern basaltic volcanism in Lesotho-Natal. In this scheme, volcanism would have started to affect the Mozambique Basin during Paleogene times (Figure 5.4, inset). Conceivably, at some point during its passage beneath the basin, the 'Quathlamba' plume could have produced enough excess melt to thicken the crust. The weak points of this explanation are that the submarine lineament has not been dated or proved of volcanic origin, and that crustal thickening centred on it is only hinted at in the relatively poorly constrained extremities of available deep-crustal seismic profiles in the basin (Leinweber et al., 2013; Mueller et al., in prep).

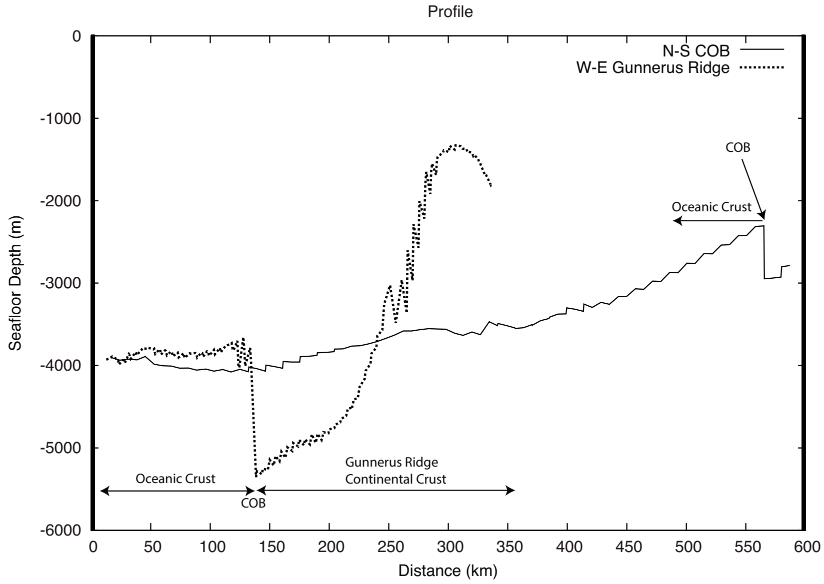


Figure 5.5: Mesozoic palaeobathymetry of the African-Antarctic corridor shows abrupt change in topography around the continent-ocean transition zone (COTZ) (solid line) and Gunnerus Ridge (dotted line). The offset along the profile is more than 1500 m at the Continent-Ocean Boundary (COB)

Within the large uncertainties, it would seem that any of a number of adjustments at one or more of various times could reasonably be applied to the palaeobathymetric models in order to correct the inconsistencies in present-day depth of the Mozambique and Riiser Larsen basins. On balance, we consider the following approach to accommodate these uncertainties most conservatively. In it, we first remove the effect of present-day dynamic topography and compensate for older modelled dynamic topography using the estimates of Müller et al. (2008b), which are similar to onshore estimates derived independently from gravity modelling by Artemieva and Vinnik (2016). Secondly, to account for the remainder of the anomalous bathymetry, we assume that the Mozambique Basin experienced a phase or phases of irreversible uplift starting around 60 Ma as a consequence of crustal thickening by excess melt supply. In the absence of more precise timing constraints on these processes and comparing it with the conjugate basement topography, we offset the modelled topography by 300-1300 m for times before 60 Ma. Assuming Airy isostasy, this offset could be equivalent to an additional crustal thickness of 3-5 km.

5.4.2 Modifications at the Continent-Ocean Transition Zone (COTZ) and Gunnerus Ridge

The modelled Early Mesozoic palaeobathymetry shows a sharp topographic step at the continent-ocean transition zones (COTZ)(Figure 5.5). These changes are related to the abrupt loss of a thermal subsidence component in the palaeobathymetric model at the step-change from oceanic to continental lithosphere implied by the age grids (Figure 5.6). Eagles et al. (2015)show that the process of identifying a precise continent-ocean boundary like this is unlikely to lead to valuable or useful results. Instead of a flattened thermal subsidence curve that terminates at a sharp step at the present day, Figure 5.6 shows that the region lying seaward of the assigned COTZ exhibits a longer-wavelength basement depth deviation from the subsidence models along both margins. As the Figure 5.was produced to model sediment-stripped basement depth by assuming an Airy isostatic response to sediment loading, it clearly indicates another process shapes the continent-ocean transition zones on both plates. This process can be assumed to be lithospheric flexure in response to loading of the COTZ by the buoyancy contrasts that exist across it as a consequence of continental attenuation and densification by mechanical and volcanic processes that culminate in the production of igneous crust. Future work might aim to produce expressions that can be used to predict curves of this nature for palaeobathymetric modelling of COTZs. The difference at the northern edge of Gunnerus Ridge is almost 1500 m (Figure 5.5). That the depth around Gunnerus Ridge is overestimated is evident from interpreted seismic profiles shows that isolated continental blocks have a different thermal behaviour than continents.

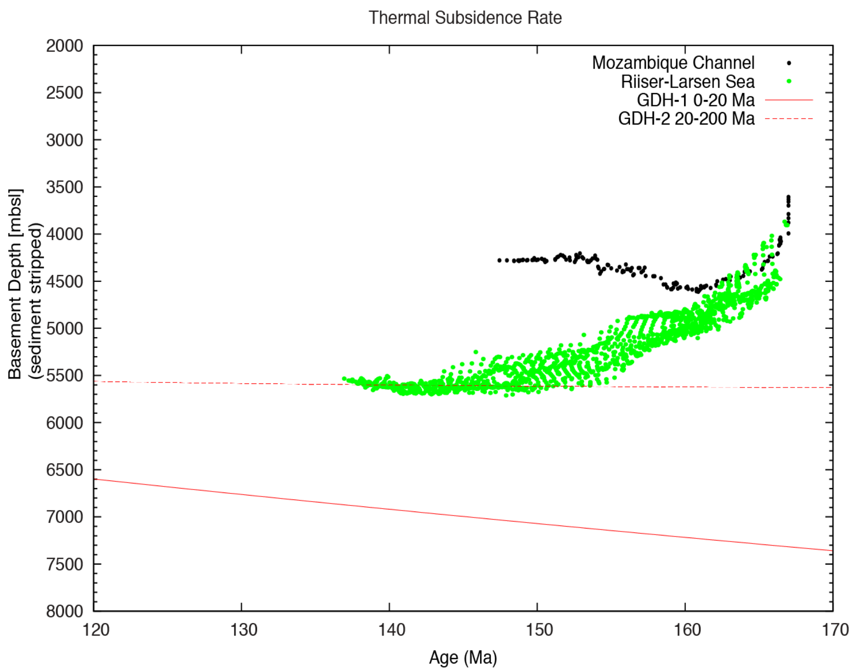


Figure 5.6: Age vs basement depth (sediment stripped) plot for Mozambique Basin (black) and Riiser-Larsen Sea (green) with depth of the basement and sediment thickness derived from seismic data. The rigid older oceanic crust bends upwards closer to the continental margin.

The retention of step artefacts like those in Figure 5.5 would have little or no upside for our model. In Figure 5.7, these artefacts are simply removed by extrapolating the oceanic crustal age into the continent-ocean transition zone and leaving the crustal thickness unchanged. The consequent maximum underestimation of the water depth on the shelf at 140 Ma, at which time the oldest crust would have been about 30 Myr old, would not exceed 300 m at the COTZ.

5.4.3 Modifications for Beira High

Beira High is a basement high located off the mouth of the present-day Zambezi. The crustal affinity of Beira High is still speculative. Watts (2001) suggests an oceanic origin whereas other authors (Mahanjane, 2012; Mueller et al., in prep; Reeves and de Wit, 2000) suggest that it is a relic of the African continent. The modelled palaeobathymetry of Beira High, assuming a continental origin of the same (Proterozoic) age as the African interior, would be much deeper than that of the surrounding oceanic crust (e.g. Figure 5.5) in models older than 100 Ma. This contradicts seismic data that show an absence of older sediments on top of Beira High and onlapping Mesozoic sequences on its flanks, suggesting it functioned as a regional high at those times (Castelino et al., 2015; Mahanjane, 2012; Salazar et al., 2013). Instead, these observations echo Watts' (2001) suggestion that the margin underwent a flexural evolution similar to that of oceanic lithosphere. Beira High might therefore be interpreted either as a thick oceanic crustal construct or as a continental block that is embedded within oceanic lithosphere. Using either assumption along with a thermal age equal to the time of rifting prior to breakup gives a palaeobathymetric evolution that is in agreement with the seismic interpretation (Figure 5.7).

5.5 Palaeobathymetric models

In this section, we describe and interpret the adjusted palaeobathymetric models.

5.5.1 Early basin developments

Figure 5.7 shows the development of a mid-ocean ridge crest between two symmetric oceanic basins 3000-4000 m deep between the conjugate margins in the period 140—100 Ma. The system is enclosed in the south by the Gunnerus and Astrid ridges with

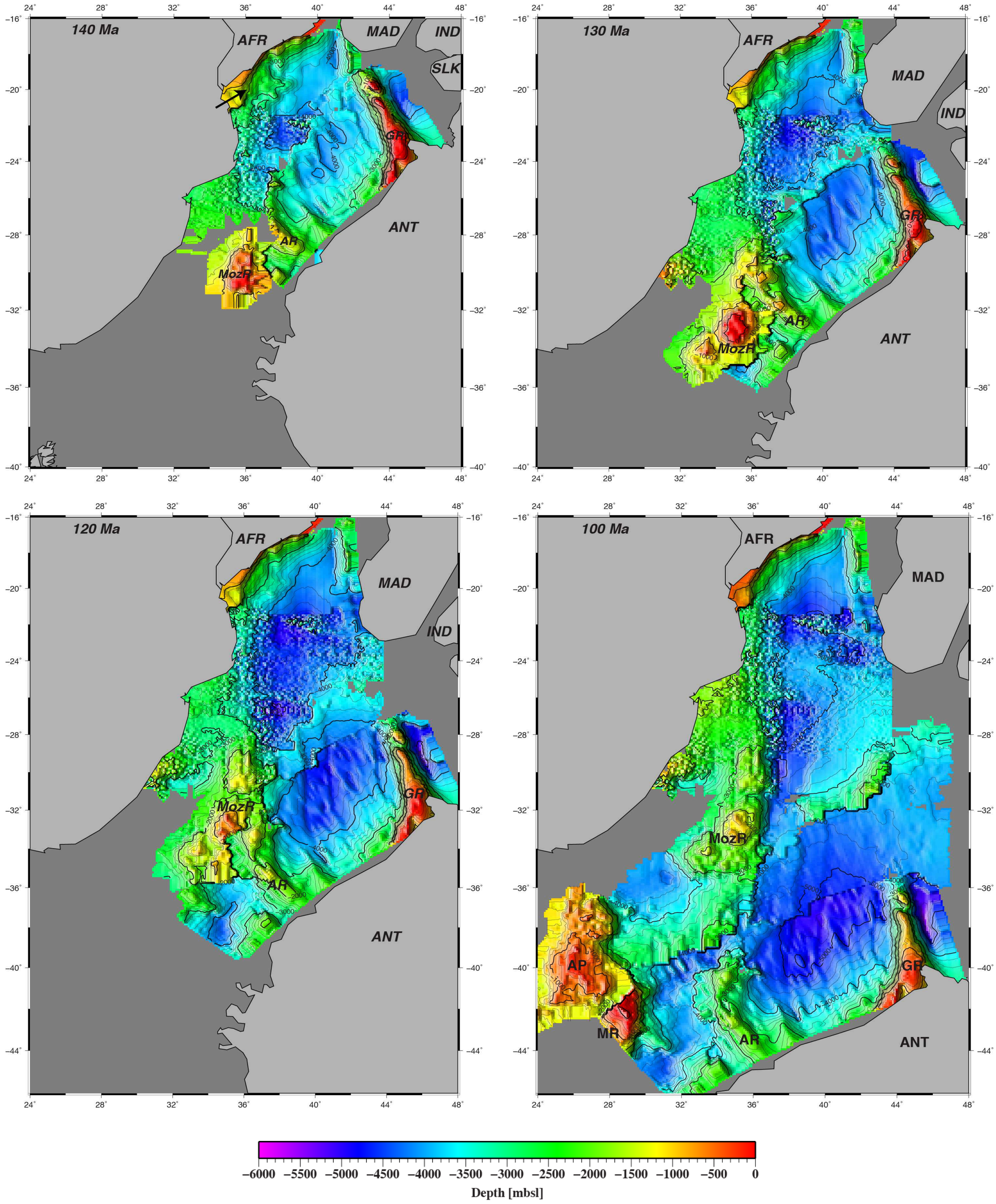


Figure 5.7:Mesozoic palaeobathymetry of the African-Antarctic corridor with Beira High as oceanic crust and offsetting Mozambique Basin by 1300 m for uplift and Dynamic topography. The black arrow indicates the direction of sediment transport from the delta into the basin. Seaward side of the continent-ocean boundary and Gunnerus Ridge is interpolated up to 30 km. Abbr: AFR= African Plate; ANT= East Antarctic Plate; MAD=Madagascar; IND= Indian Plate; SLK= Sri Lankan Plate; BH= Beira High; MB= Mozambique Basin; RLS= Riiser-Larsen Sea; GR= Gunnerus Ridge; AR= Astrid Ridge; MOZR= Mozambique Ridge; AP= Agulhas Plateau

palaeo-water depths shallower than 1000 m. As the opening of the Mozambique Basin/Channel progresses, the emplacement of Mozambique Ridge (140-122 Ma) continues to shut the basin off from the region further south. Subsequent creation of a Large Igneous Province (LIP) comprising the NE Georgia Rise, Maud Rise and Agulhas

Plateau (Gohl and Uenzelmann-Neben, 2001; Gohl et al., 2011) continues to enclose the basin in the south until at least 95 Ma.

Primary sediment transport originates from the shelf off the Mozambique flood plains into the Mozambique Basin via the narrow passage between the Mozambique continent margin and Beira High (black arrow in Figure 5.7-140 Ma). Sediments are primarily deposited along the entire shallow southern edge of the basin including African coast, Mozambique Plateau/Ridge, Astrid and Antarctic margin and the basin trough located in the northeast. The difference in the sediment influx from the two continents is already visible in the two basins with the seafloor depth of the Riiser-Larsen Sea, at 5400 m, much deeper than the more heavily-sedimented Central Mozambique Basin at 4800 m.

5.5.2 Late Cretaceous bottom current circulation

Castelino et al. (2015) and Coffin et al. (1986) suggest the initiation of bottom currents and associated contourites along the Eastern African margin during the Late Cretaceous. A gateway for bottom currents turning towards the South Atlantic started to form in response to rifting of the Maud-Agulhas-NE Georgia Rise LIP around 85 Ma (Gohl et al., 2011; Pérez-Díaz and Eagles, 2014). Figure 5.8 shows the palaeobathymetry and the separation of Agulhas Plateau and Maud Rise. It can be seen that a narrow deep passage formed between the topographic high of the spreading-ridge axis and Agulhas Plateau around 70 Ma could allow water-mass exchange between the Mozambique Channel and South Atlantic Ocean. However, evidence for bottom current activity suggests it started in the intervening Transkei, Agulhas and Cape basins tentatively during the Eocene or Early Oligocene (Schlüter and Uenzelmann-Neben, 2008; Tucholke and Carpenter, 1977). The apparent contradiction might be interpreted in terms of components of the East African current that bypassed the Transkei Basin southwards through the Riiser Larsen Sea, and/or were deflected eastwards into the proto-Tethys Ocean.

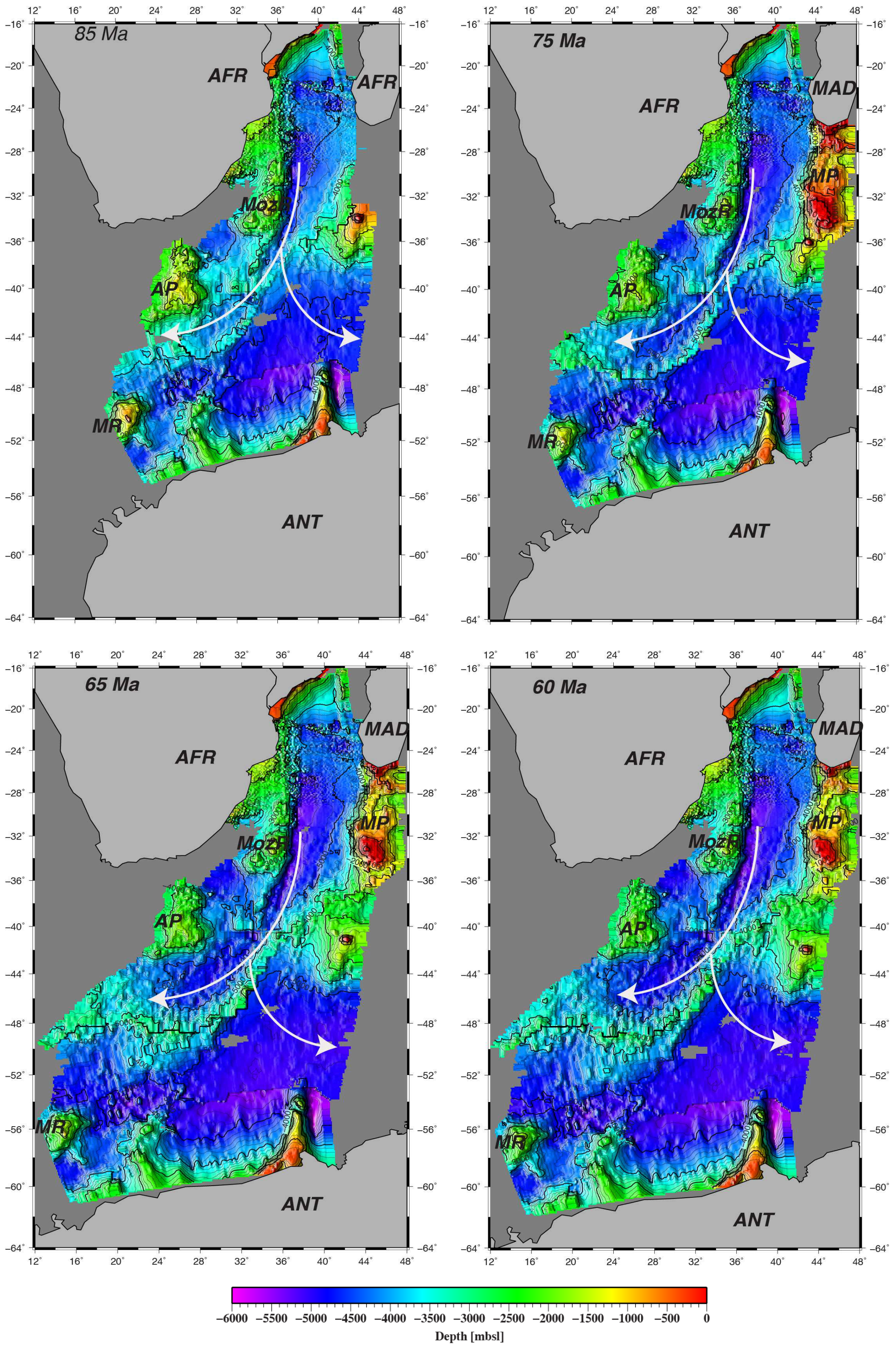
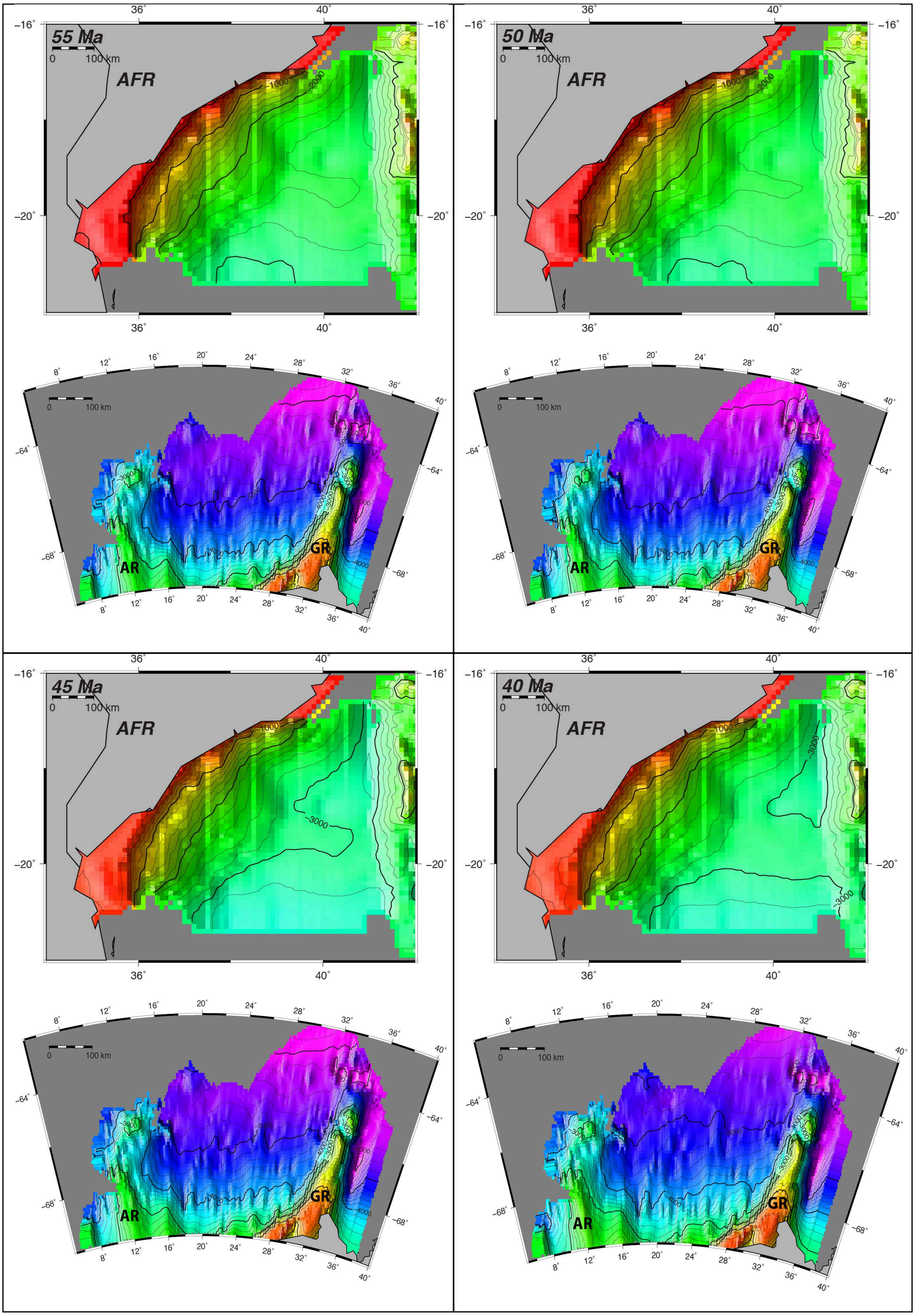


Figure 5.8:Early Cretaceous palaeobathymetry showing the opening of the passage between Agulhas Plateau and Southwest Indian Ridge connecting Mozambique Channel to Southern Atlantic Ocean. The white arrows indicate the possible pathways fro bottom current. Abbr: AFR= African Plate; ANT= East Antarctic Plate; MAD=Madagascar; MB= Mozambique Basin; RLS= Riiser-Larsen Sea; GR= Gunnerus Ridge; AR= Astrid Ridge; MOZR= Mozambique Ridge; AP= Agulhas Plateau; MR= Maud Rise; MP= Madagascar Plateau

5.5.3 Cenozoic basin evolution

Within the limits of resolution of the model, the character of the regional relief remains fairly stable on both margins during the Cenozoic (Figure 5.9). The seafloor depth in the Mozambique Basin constantly decreases through Cenozoic times as the shelf progrades into the channel, without changing its general morphology. The massive Zambezi submarine fan oriented eastwards and then southwards into the Mozambique Channel is the most prominent feature through the Cenozoic until the Quaternary creating a ponded basin in the northeast. In the Riiser-Larsen Sea, the 4000 m and 5000 m isobaths remain fairly constant with brief northward excursions at 40-45 Ma (Glacial onset??), 30-35 Ma (Global -eustatic sea level drop??) and 10-15 Ma (middle Miocene climate transition??) (Figure 5.9). This can be attributed to an increased influx of glacio-marine sediments during the onset of glaciation during Paleogene (Figure 5.10). The abundant sediment supply from the continental shelf to the deep-marine environment by ice-sheet advances has been recognized in seismic reflection profiles (Kuvaas et al. 2004). The mid-Oligocene glacial-eustatic sea level drop has been recognized on margins globally and its effect is also observed on the Mozambique Basin and the Riiser-Larsen Sea. The change in seafloor depth in the Riiser-Larsen Sea during the middle Miocene can be explained by climate transition from ~16 to 14.8 Ma (Miller and Fairbanks, 1983) that was marked by several short term variations in global climate, sea level, ice sheet volume and ocean circulation.

The trends of sedimentation rate at the conjugate margins (Figure 5.10) in the Mozambique Channel and the Riiser-Larsen Sea are comparable during the Mesozoic. They deviate from one another when episodic tectonic activity (Burke, 1996; Partridge and Maud, 1987)on the African plate drives the influx of sediments on the Mozambique margin since 90 Ma and glaciation starts to affect the Riiser-Larsen Sea since Paleogene.


55 Ma
AFR
AR
GR
50 Ma
AFR
AR
GR
45 Ma
AFR
AR
GR
40 Ma
AFR
AR
GR

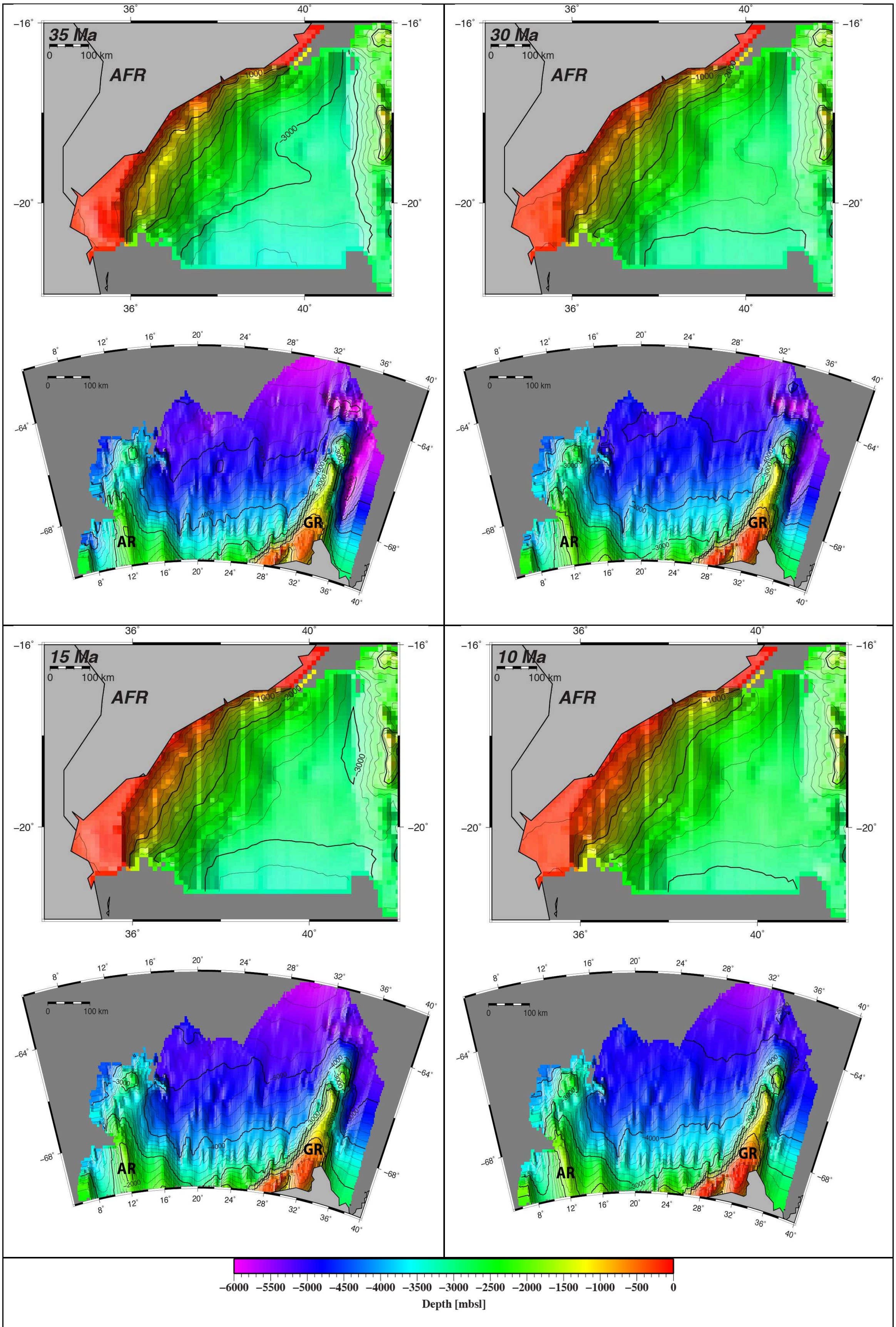


Figure 5.9:Cenozoic palaeobathymetry off Mozambique and the Riiser Larsen Sea with present-day coordinates. Abbr: AFR= African Plate; RLS= Riiser-Larsen Sea; GR= Gunnerus Ridge; AR= Astrid Ridge;

5.6 Conclusions

We present new palaeobathymetric model grids for multiple time slices since the early phase of separation between Antarctica and Africa (140 Ma). Our regional reconstruction is well constrained by different regional geophysical data sets: the sediment thicknesses are calculated from seismic data with depth-time constraints for the different seismic units, and the basemaps are created using the latest plate kinematic model for the African-Antarctic corridor.

The oceanic basement depths display clear asymmetry. We give the first conclusive evidence of a regional positive bathymetric anomaly in the Mozambique Basin that measures up to 1300 m. Although similar in magnitude to some estimates of Pliocene and later uplifts of neighbouring South Africa and Madagascar that have been widely attributed to dynamic support of the lithosphere by mantle convection, it cannot explain all of the details of the anomaly observed in our models in the Mozambique Basin. We speculate that the majority of the anomaly has its cause in crustal addition by excess melting related to the passage of the basin over a region of warm mantle that also gave rise to the Almirante Leite- Bassas da India volcanic lineament. Further work should be directed towards proving the timing and the source of this volcanism.

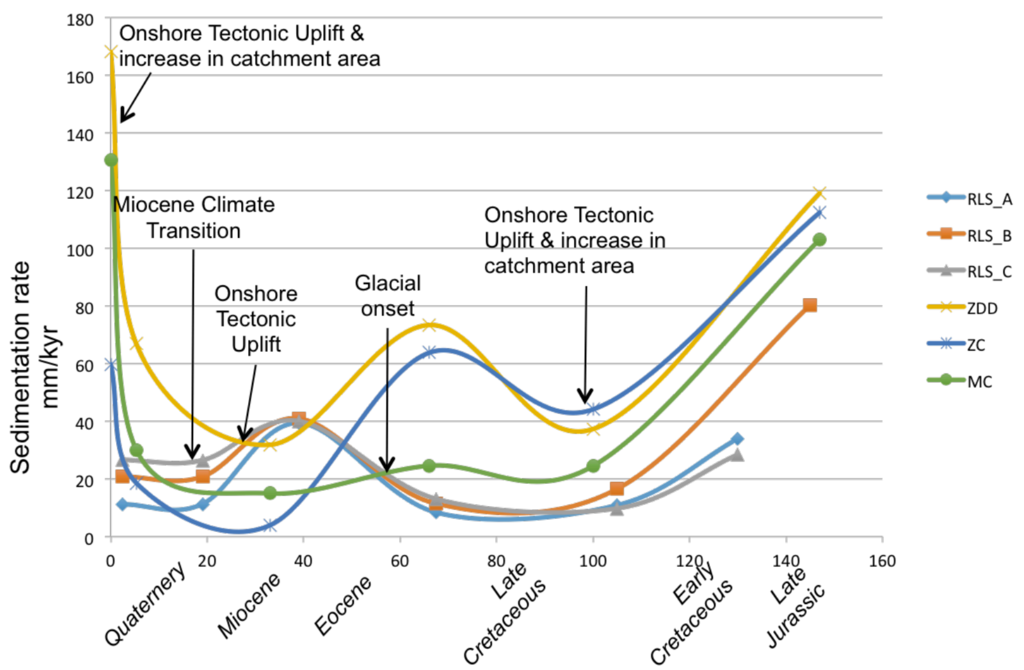


Figure 5.10:Sedimentation rate at different locations in the Mozambique Basin and Riiser-Larsen Sea. Refer to Figure 5.1 for location.

Flexure of oceanic crust plays an important role at continent-ocean boundaries. Here, it deviates from the classic age-depth relationship for thermal subsidence and maybe an expression of the physical and mechanical properties determined by the margin-type. The half- wavelength of the flexure is approximately 60-80 km with an amplitude of up to 1500 m. This flexure has to be incorporated for models older than 100 Ma when the oceanic crust at the COTZ is younger than 70 Myr otherwise thermal subsidence is overestimated.

The thermal subsidence of isolated breakup-related topographic elevations/elevated crustal blocks like Beira High and around Gunnerus Ridge can be modelled with subsidence rates that mimic those of oceanic crust similar in age to the breakup.

The morphology of Riiser-Larsen Sea has remained quite stable since its formation. There are small observable changes in depth of the modelled seafloor during glacial onset, global sea level drop and mid-Miocene climate transition, but the morphology remains largely unchanged within the limits of the resolution.

Finally, our palaeo-bathymetric model provides important constraints on ocean circulation in the Mozambique Channel during the Late Cretaceous that largely influences the commencement of along-shore bottom currents and associated contourite deposition.

5.7 Acknowledgements

We gratefully acknowledge the contribution of PMGE-VNIIOkeangeologia for the seismic data used in Riiser-Larsen Sea made available through Antarctic Seismic Data Library System (SDLS). Part of the study has been funded by the Deutsche Forschungsgesellschaft (**DFG-Project JO 191/4-1, GEPARD).** All maps were created using GMT 5.0 (Wessel et al., 2013).

Chapter 6: Controls on ancient and modern turbidite systems of the Zambezi in the Mozambique Basin

Authors:

Jude A. Castelino[1], Christian Reichert[2], Wilfried Jokat[1]

[1]*Alfred Wegener Institute, Hemholtz Centre for Polar und Marine Research (AWI), Am Alten Hafen 26, D-27568, Bremerhaven, Germany*

[2]*Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover*

In preparation for Marine Geology

Keywords

Mozambique Fan, turbidite systems, African Uplift, Mozambique Channel, Zambezi Valley, channel-levee complex.

6.1. Abstract

The 1800 km long and 400 km wide Mozambique Fan spread out in the Mozambique Channel is one of the largest submarine fans, comparable in size to the Indus Fan. Multichannel seismic profiles in the previously unexplored parts of the Mozambique Basin reveal multiple feeder systems of the upper fan that have been active concurrently or consecutively since Late Cretaceous. We identify two buried ancient turbidite systems of the Zambezi River off Mozambique in addition to the previously known Zambezi-Channel system and another speculated active system. The oldest upper fan located north of the present-day Zambezi mouth was active since Late Cretaceous when regional tectonic uplift resulted in local sea-level change and a subsequent increase in sediment influx that continued until as late as Eocene during which time the fan migrated southwards under the influence of bottom currents. After the mid-Oligocene marine regression, the Beira High Channel-levee complex fed the Mozambique Fan from the southwest until Miocene times, with reworking of sediments from the shelf and continental slope to the distal abyssal fan. From the Miocene until Pliocene, sediments have bypassed the shelf and upper fan region through the Zambezi Valley system directly into the Zambezi Channel. Presently, several valleys oriented in the NW-SE direction, indent the seafloor on the shelf and continental rise that transports sediment to the outer Mozambique Fan.

6.2. Introduction

Interpretation of turbidite systems from modern and ancient deposits has shown that channel and channel-related features dominate near shore and delta regions of rivers (Mutti and Normark, 1991). Large river-fed turbidite systems (e.g. Amazon, Mississippi, Bengal, Indus, etc.) dominate fan development at continental slopes that extend over 1000 km and are more than 100 km wide (Weimer and Link, 1991). Studies of numerous modern and ancient fans over the last four decades to understand the controls on fan development and morphology led to detailed characterization of their architecture and the pattern of facies distribution (Bouma et al., 2012; Weimer and Link, 1991). The size shape and orientation are influence

Fan	Length (km)	Width (km)	Area (sq.km)	Max Thickness	Water depth apex (m)	Water depth distal (m)
Bengal and NIcobar	3800	2000	?	16500	1400	5500
Indus	1500	<960	1100	>9000	1500	4600
Mozambique	1800(1)	400(1)	?	8000 (2)	1600(2)	5000(2)
Amazon	>700	250-700	330	4200	1500	4800
Mississippi	540	570	>300	4000	1200	3300
Monterey	400	250	75	2000	1280	4570
Astoria	>250	130	32	2200	1140	2840
La Jolla	40	50	1.2	1600	550	1100

Table 6.1: Dimensions of some well-studied modern-day fans (source: Curray et al., 2002) and the dimensions of Mozambique Fan (1) (Kolla et al., 1980) (2) (Castelino et al., 2016; this study)

by several environmental parameters. Tectonics, sediment type and supply, and sea-level variations are the primary control on the morphology of the fan. While some fans are well studied (e.g. Amazon, Bengal, Indus Crati, Mississippi fans), the Mozambique Fan continues to remain poorly studied despite its size (Table 6.1), and the significance of the Zambezi River that erodes vast quantities of sediment (100 Mio tonnes annually) from the hinterlands of southern Africa (Kolla et al., 1980; Walford et al., 2005). Only shallow geophysical and coring-based studies have investigated the upper (Droz and Mougenot, 1987) or middle and lower (Kolla et al., 1980) parts of the fan The Mozambique Fan occupies the Mozambique Channel, a north-south trending depression that is bounded by the African Margin to the west and Madagascar Margin and Davie Ridge to the east, and that opens into the Agulhas Basin in the south. Droz and Mougenot (1987) describe how the Mozambique Fan is supplied with sediments via a channel system that begins as a series of valleys on the African and Madagascan shelves (e.g. the Zambezi, Serpa-Pinto, Limpopo-Save, Labathie and Tsirihibina valleys; Figure 6.1). They divide the eastward flowing Zambezi turbidite system originating on the Mozambican shelf in three parts, namely, (1) network slope incising Zambezi Canyon

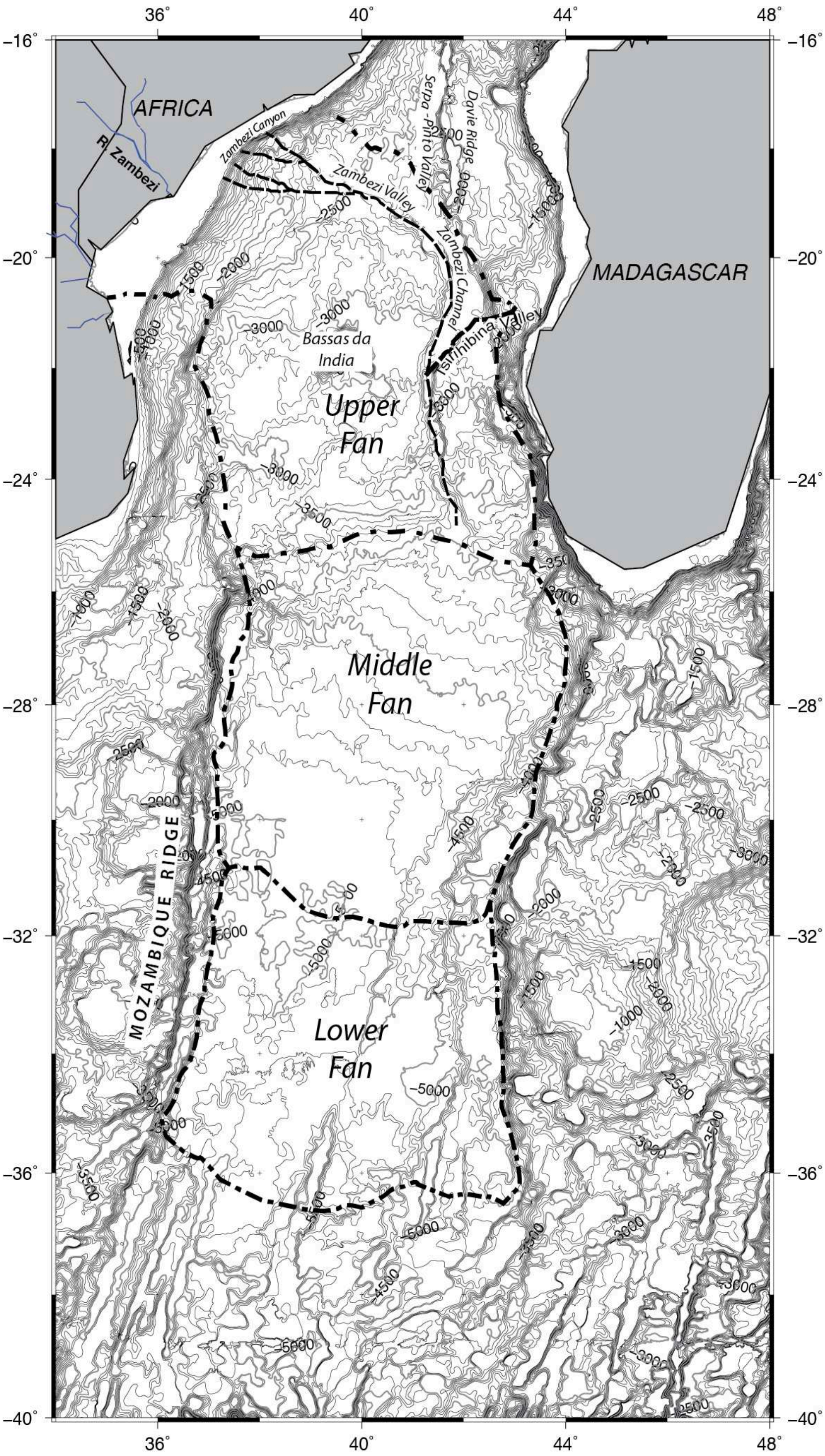


Figure 6.1: GEBCO Bathymetric map of Mozambique Basin showing the extent (dot-dash line) and different parts of the Mozambique Fan (identified by Kolla et al., (1980). The depressions of the Tsiribihina, Serpa-Pinto and Zambezi Valleys that feed the Upper Mozambique Fan can be observed in the bathymetry. The Zambezi Channel (dashed line) with a broad meander disperses into the Middle Fan.

that precedes (2) the Zambezi Valley on the continental rise that erodes the top sediment layers and meanders south at 41°E before (3) giving way further downstream to a stable, almost meridionally linear feature termed the Zambezi Channel. The Zambezi Channel displays features typical of a channel-levee system with thick sediment deposits on either side of the channel. The valley appears to be inactive and infilled with chaotic or sheeted sediment deposits.

The objective of this study is to understand the triggers and controls on the turbidite and fan development in the basin, based on its morphology. Tectonic settings, sea-level variations and sediment supply and type are the primary controls on fan evolution and morphology (Stow et al., 1985). It has been well-established that the African plate has been subjected to repetitive episodes of tectonic activity (Burke, 1996; Partridge and Maud, 1987; Partridge, 1998) and strong variations in sediment supply to the basin (Castelino et al., 2015; Walford et al., 2005). We use 9 interpreted multi-channel seismic profiles totalling 2200 km in length and ship-borne bathymetry data acquired in 2007

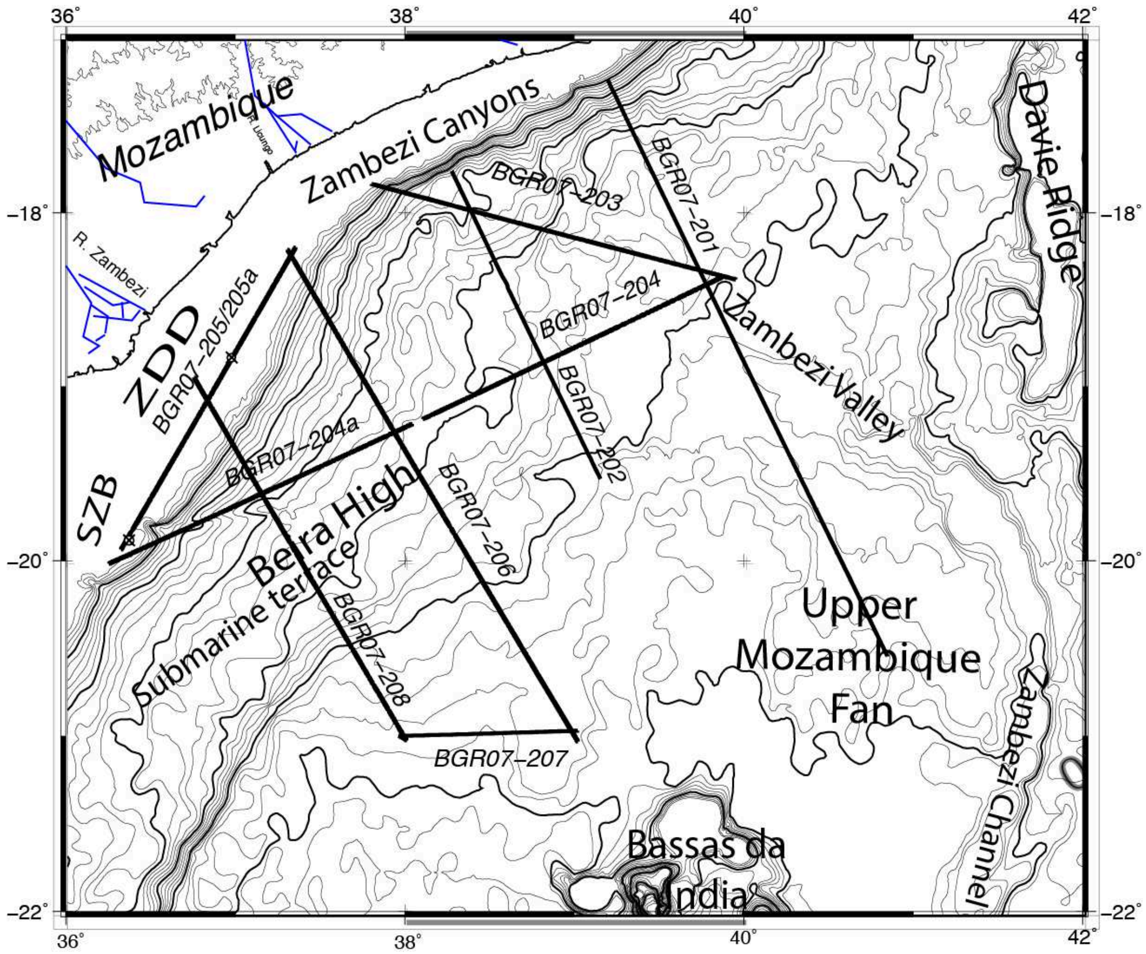
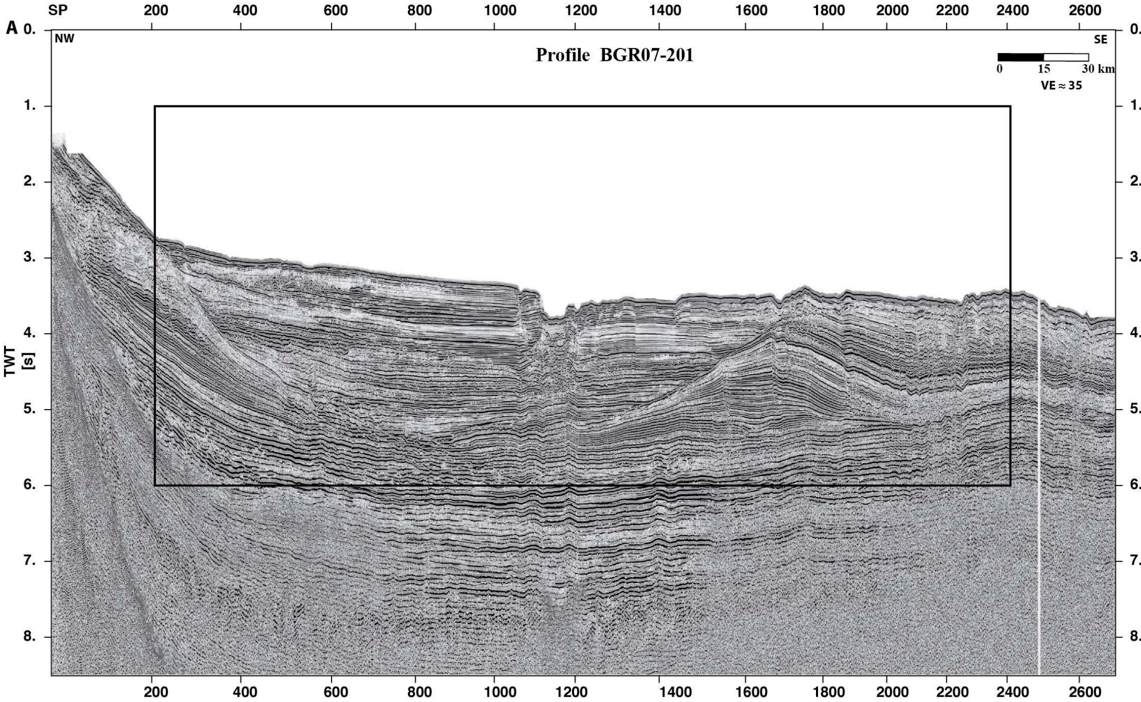


Figure 6.2: Location of the seismic lines used in this study. The Sofala-Zambesia Bank (SZB) forms a prograding sequence over the Zambezi Delta Depression (ZDD).

(Castelino et al., 2015; Reichert, 2007) along with a global bathymetric grid (GEBCO) to examine the morphology of the ancient and modern turbidite systems at different times since Late Cretaceous. Litho-stratigraphic information is used from previous studies (Castelino et al., 2015; De Buyl and Flores, 1986; Droz and Mougenot, 1987b). The seismic units labelled MBSU 1 - 6 correspond to Jurassic, Lower Cretaceous, Upper Cretaceous, Paleogene, Miocene and Quaternary sediments respectively.

6.3. Morphology of the ancient turbidite systems

The part of the Upper Mozambique fan originating from the Zambezi comprises of at least three prominent pathways that were successively active since Late Cretaceous. (1) The oldest of these pathways is located to the north of the Zambezi and was active in the Late Cretaceous until at least Eocene. We refer to its deposits as the Zambezi Fan (Figure 6.3-6.5). (2) After Oligocene, the sediment delivery system switched to the south over the Sofala Zambesia Bank through valley incision and channels. The Sofala Zambezia bank represents the present-day shelf that has prograded and aggraded since Miocene times. Further downslope this system forms a large channel-levee complex on the submarine terrace over Beira High. We term this feature the Beira High Channel-levee Complex (Figure 6.6 and 6.7). (3) Since Late Miocene, a significant part of the sediment load from the Zambezi was delivered via the Zambezi Valley directly to the Mozambique fan in the deeper basin by bypassing the shelf (Figure 6.1-6.5). The Late Cretaceous - Eocene Zambezi fan is located north of the present-day Zambezi River mouth off the foot of the continental shelf (Figure 6.7A). It overlies the continuous Lower Cretaceous unconformity. The evolution of the fan can be interpreted in profiles BGR07-201, BGR07-202 and BGR07-203. Close to the shelf edge, several valleys or channels are interpreted from their fills and slope-apron deposits (BGR07-203). The dispersal of sediments via lobes of the basal floor fan (BFF) is interpretable in BGR07-202 (Figure 6.4), in the form of a number of lenticular convex-upward sediment wedges (4-6 s TWT). In BGR07-201, several of these mounds are located in the deeper channel where they are juxtaposed with mass wasting deposits originating on the continental rise (Figure 6.3: 5-5.5 s TWT). The depo-centers of the younger sediment wedges reveal that they migrated southwards. While the northern fan lobe grows slowly, the southern fan lobe aggrades and migrates southwards making an almost triangular shape (Figure 6.3 : SP 1400-2200).



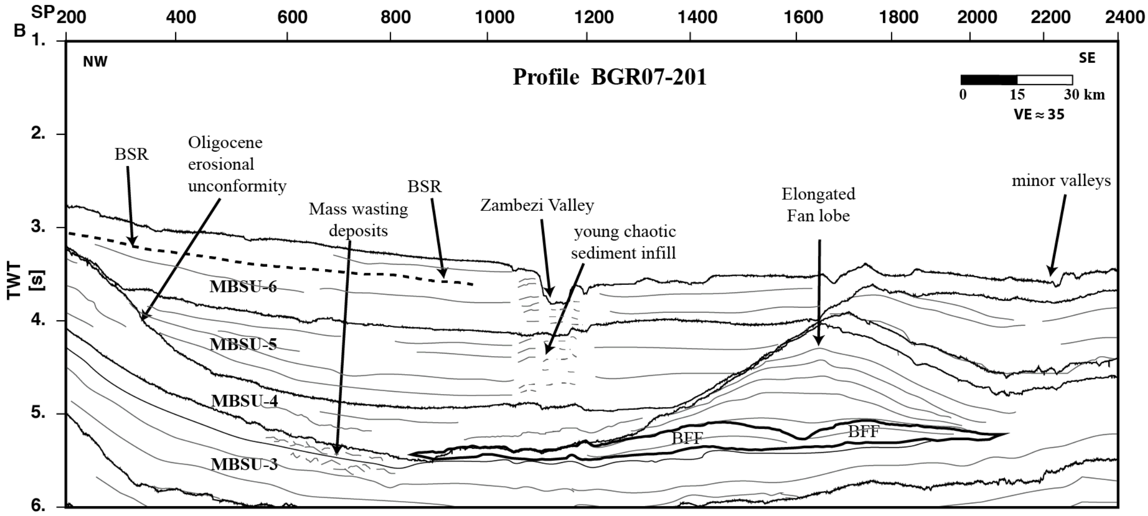
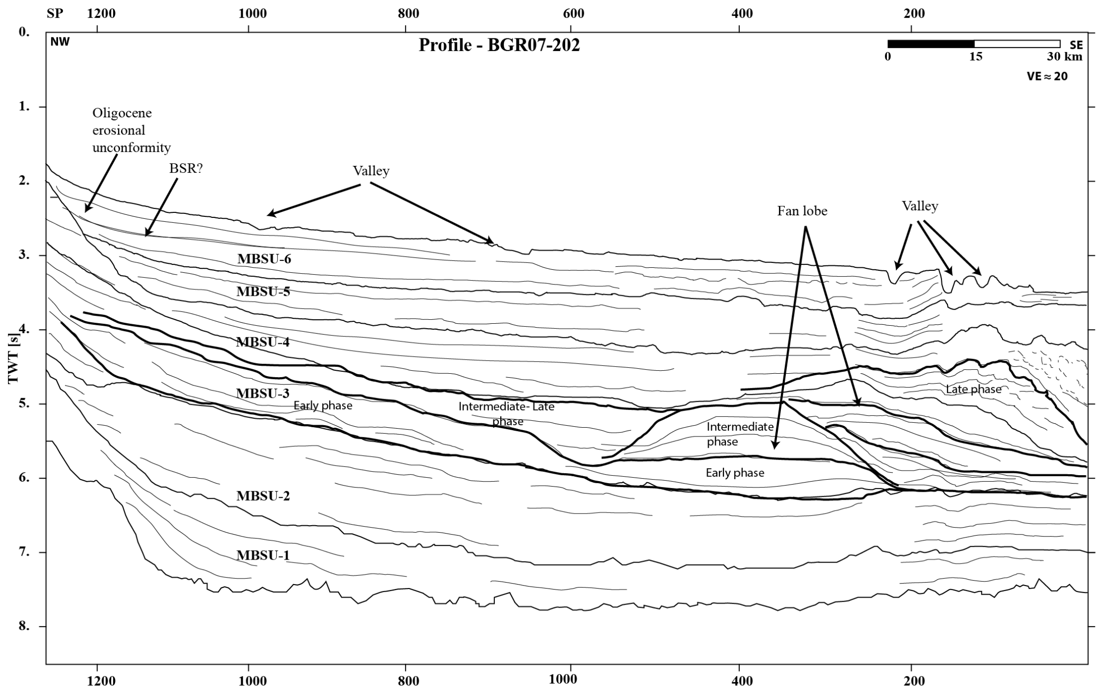


Figure 6.3: (A) Uninterpreted seismic profile of BGR07-201. The black box indicates the extent of the interpreted section. (B) Line drawing of interpreted seismic Profile BGR07-201 (modified from Castelino et al, 2015). Submarine fan development begins in unit MBSU-3 where mass wasting deposits are followed by development of Basin Floor Fans (BFF). The Zambezi valley that fed the Upper Mozambique Fan is characterized by steep walls, slope failure faults and chaotic sediment infill.



ure 6.4: Line drawing of interpreted seismic profile BGR07-202 (modified from Castelino et 2015). Most of MBSU-3 unit comprises of fan lobes. During the early phase when tectonic vity exerts primary control fan development, the lobes have comparable development. During later phase when sediment supply is the primary control, the right (southwestern) lobe umulates faster and migrates southwards under the influence of bottom currents. The seafloor is sed by valleys at several locations that transport sediment load from the shelf into the channel.

The Beira-High Channel-levee complex structure is observed in profiles BGR07-206 and BGR07-208 (Figure 6.6-6.7; 3-5 s TWT). Both profiles show two distinct depositional patterns. The lower deposits (Phase 1) are composed of several channels and smaller submarine fan lobes that overlie canyons that were incised during the mid-Oligocene marine regression. In the upper unit (Phase 2), a single deep incising valley with high levee deposits is observed. Simultaneously prograding-aggrading clinoforms at the shelf with turbidity deposits onlap the levee flanks. The deep channel is filled in with well-stratified sediment deposits. The morphology of the Zambezi Channel (Figure 6.1-6.2) is very well defined in the satellite-derived bathymetry. Contrary to the previous study of Droz and Mougenot (1987), ship-borne bathymetry reveal several tributary valleys that converge into a single valley (Figure 3) around 40°E (referred to as Zambezi Valley) where it starts to behave like a channel-levee system (referred to as Zambezi Channel) with thick sediment deposits on either side. The valley erodes the Miocene and younger sediments and is characterized by steep walls and slope failures. The valley itself appears to be infilled with chaotic or sheeted sediment deposits. On the shelf edge, several closely spaced canyons (Zambezi Canyon) sharply incise the seafloor (Figure 6.9). These canyons merge into subtle valleys on the continental rise and are predecessors to the Zambezi Valley.

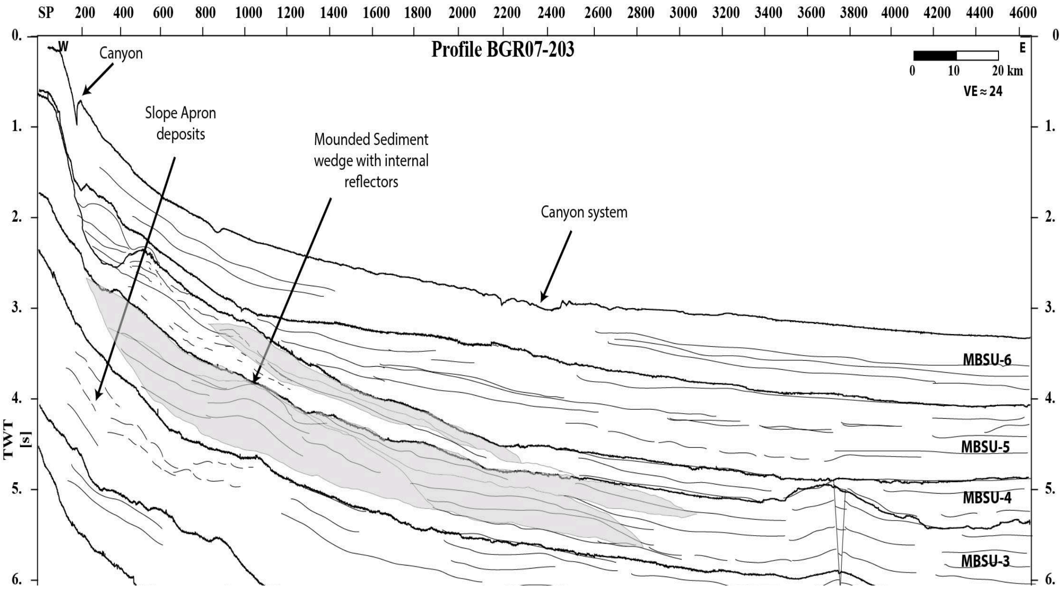


Figure 6.5: Line drawing of seismic line BGR07-203. Sediment mounds associated with slope-apron submarine fan deposits are observed in the section. Shelf incising canyons are located on the seafloor

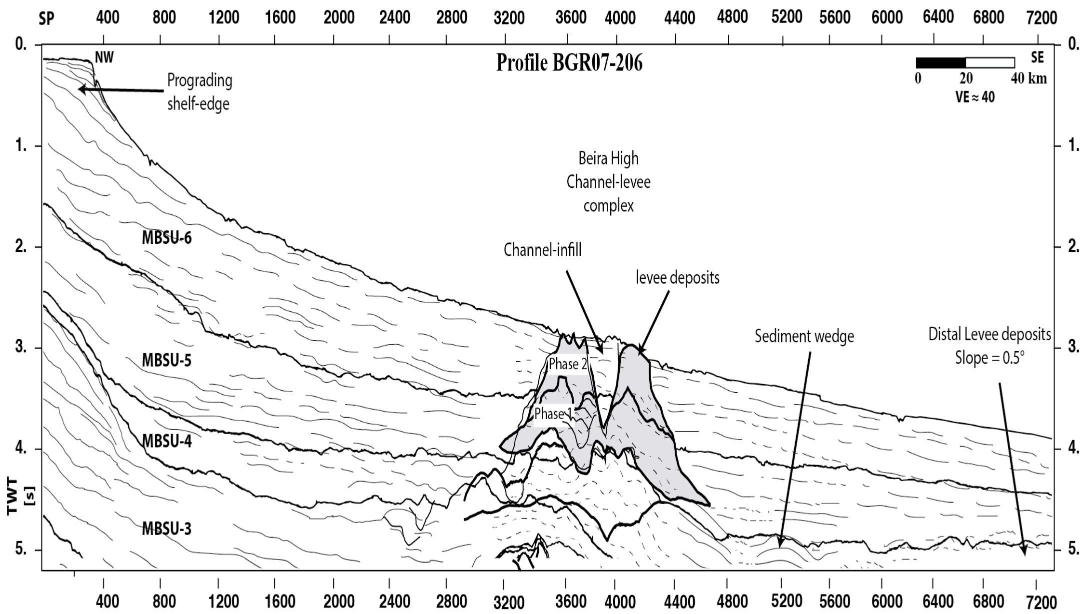


Figure 6.6: Line drawing of seismic line BGR07-206. The top-MBSU-4 reflector outlines several incised valleys that are filled with younger sediments. The massive Channel-valley complex above Beira High is illustrated in a grey shade

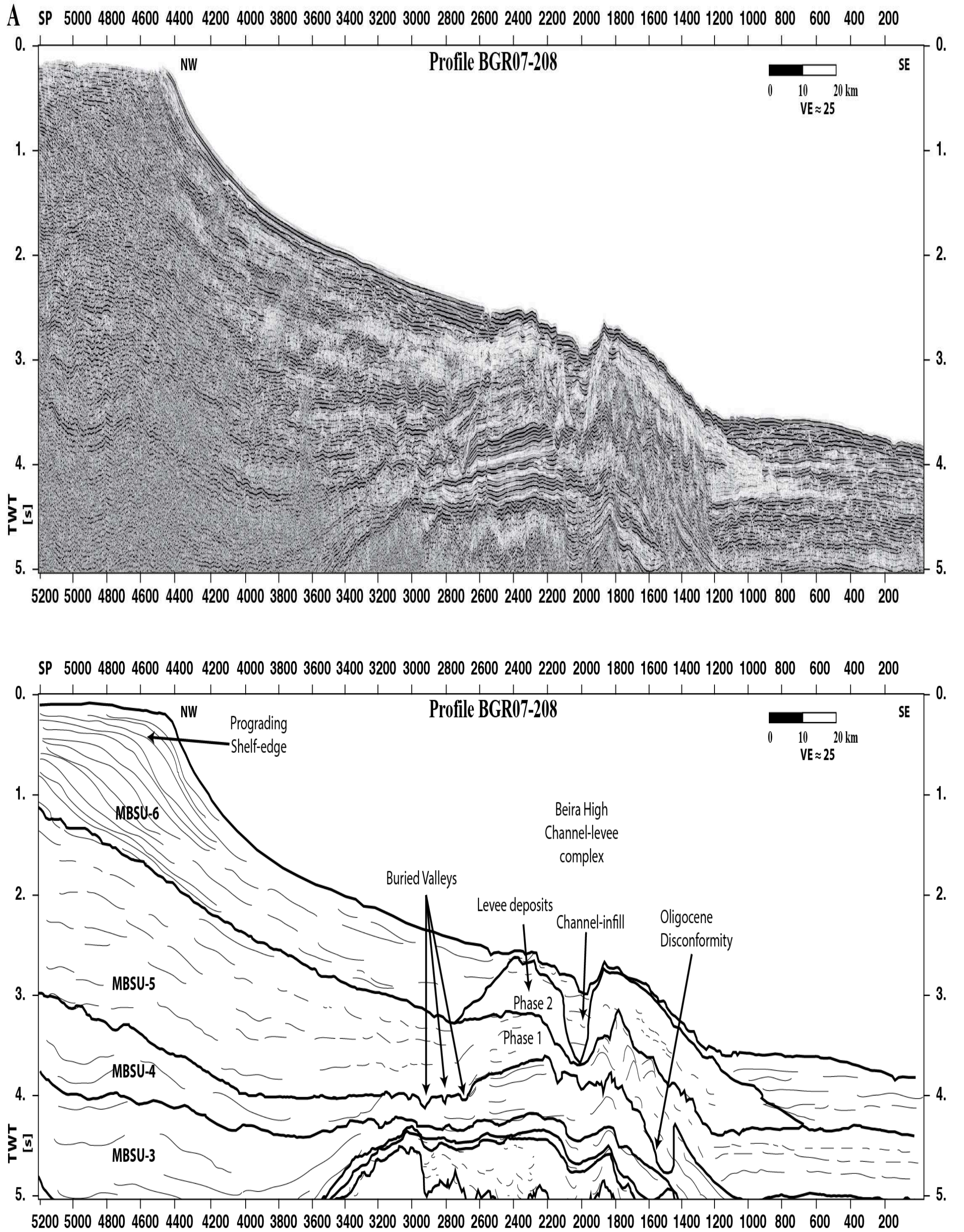
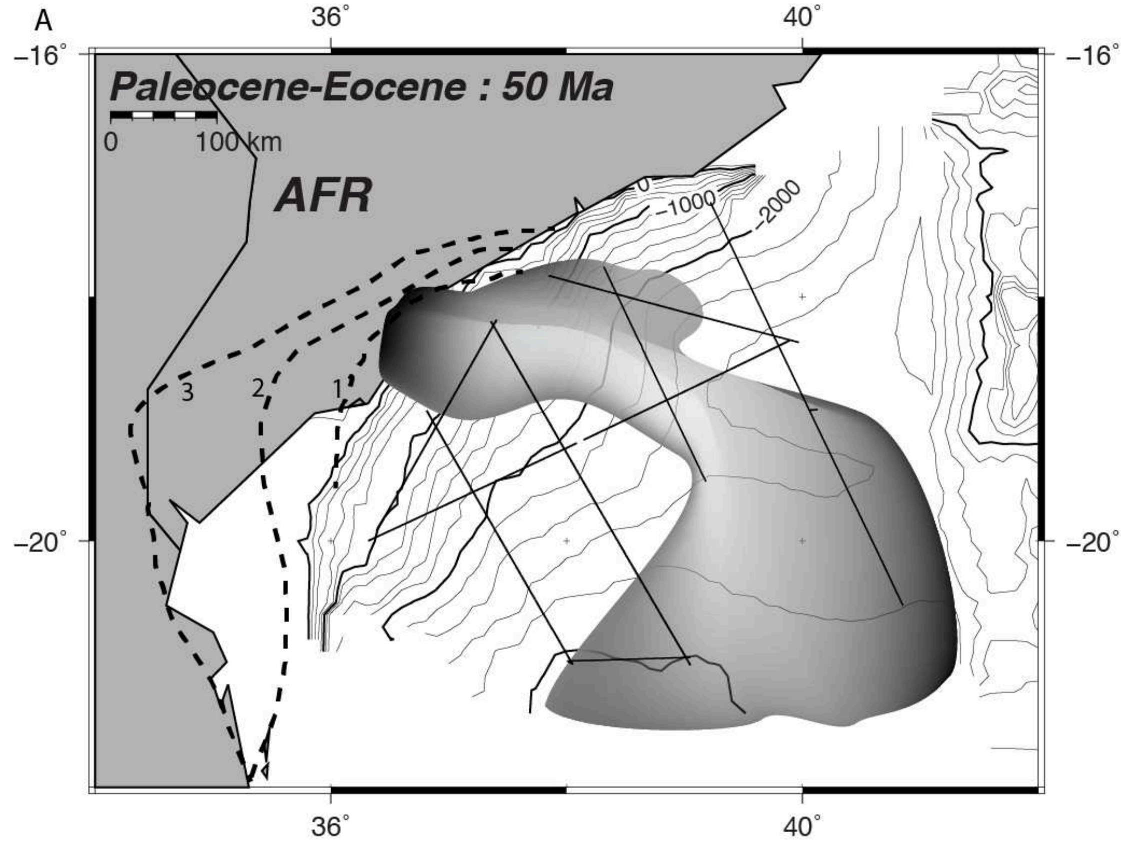


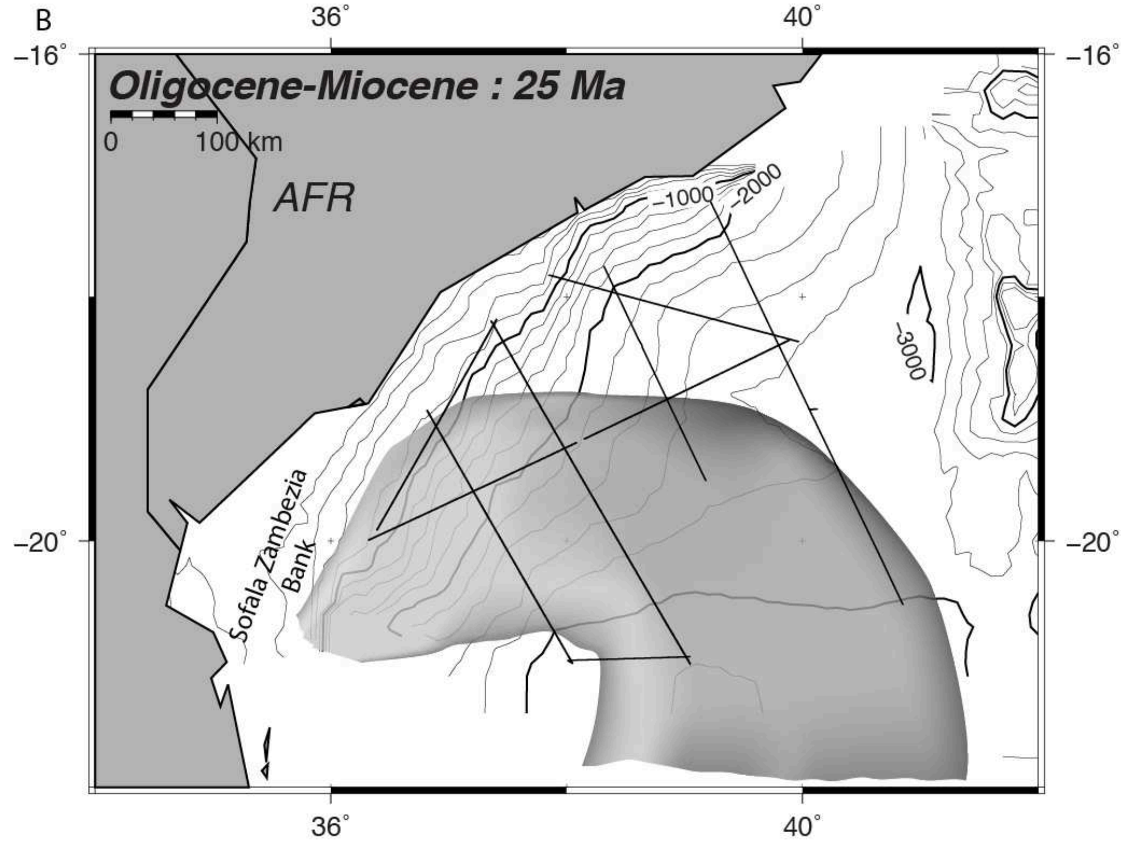
Figure 6.7: (A) Uninterpreted seismic profile of BGR07-208. (B) Line drawing of seismic line BGR07-208 showing the continuation of the Channel-valley complex above Beira High. The top reflector of MBSU-4 is heavily eroded unconformity and younger chaotic sediments fill the erosive topography. To the east, deep-sea sedimentation onlaps the levee deposits.

6.4. Controls on Late Cretaceous – Eocene fan development

Epeirogenic uplift of the African continent due to tectonic activity, inferred from onshore landscape analysis (Partridge and Maud, 1987), is estimated to have raised the continent by about 1000 m around 90 Ma. This most likely resulted in a regional change in sea level over a span of few million years. Slope failures along the continental shelf, like those interpretable in the northern profile BGR07-201 (Figure 6.3) from mass wasting deposits on the continental rise, were the first response to the resulting decrease in accommodation space and oversteepening of the continental slope. Besides these slope failures, basin floor fans developed at the continental rise where they were fed by shelf canyons and gullies with sediments eroded from the shelf. We refer to the mass wasting deposits and Basin Floor Fan (BFF) development as early phase of fan development that is controlled directly by tectonic activity.

The seismic lines of our study cover only the lower fan deposits. Onshore studies based on well data show the presence of fan deposits comprising sandy sediments (De Buyl and Flores, 1986; Nairn et al., 1991; Salman and Abdula, 1995) that indicate the Palaeocene-Eocene shelf edge and Zambezi Fan were located much further landwards (Figure 6.7A). Other consequences of the Late Cretaceous African uplift were a change in the African topography and increase in catchment area of the Zambezi. Previous studies have shown that the consequent increase in the sediment influx (Castelino et al., 2015; Walford et al., 2005) led to the deposition of upper or middle –fan deposits until Eocene over the older deposits of the lower fan as it grew further into the channel (Figure 6.3-6.4). We refer to these deposits as 'Late phase' of fan development where sedimentation volume and type is the primary control on the fan development. The elongate shape of the fan during the second phase also indicates to a high rate of sediment supply with mixed size grade from a single primary source (Stow et al., 1984), in this case, the Zambezi River. Upslope, the south-western (right) fan lobe shifted southwards by discrete steps while the accumulation on the northeastern lobe was significantly less (Figure 6.3-6.4). This is most likely a combined effect of shelf margin build-up moving landward after the post-uplift subsidence and the influence of a north-south bottom current.


A
36°
40°
−16°
−16°
Paleocene-Eocene : 50 Ma
0
100 km
AFR
0
−1000
−2000
3
2
1
−20°
−20°
36°
40°


B
36°
40°
−16°
−16°
Oligocene-Miocene : 25 Ma
0
100 km
AFR
−1000
−2000
−3000
Sofala Zambezia
Bank
−20°
−20°
36°
40°

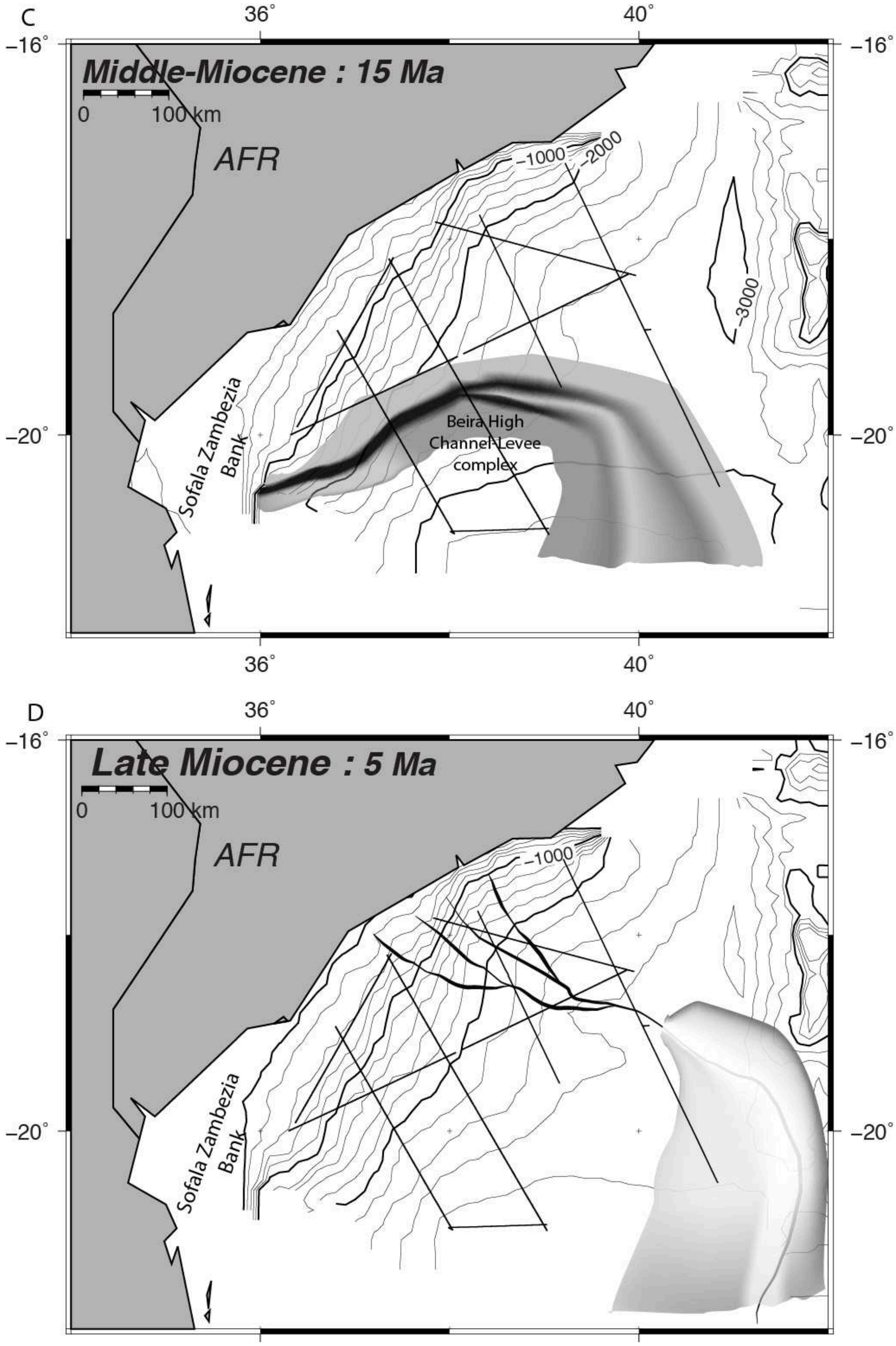


Figure 6.8: Schematic sketch of the submarine fan and turbidite systems. The contour lines show the palaeo-bathymetry for the given age (Castelino et al., 2016) [A] Morphology during Paleocene - Eocene. The dashed lines indicate retreating palaeo-shelf edge (De Buyl and Flores, 1986) 1- Paleocene; 2- Early Eocene; 3- Middle-Late Eocene. [B] Turbidite system during Late Oligocene -Early Miocene switched further south. [C] Beira High Channel-Levee complex during middle-Miocene. Dark grey shading indicates location of the channel. [D] Pathways of the Zambezi Valley feeding the Upper Mozambique Fan during Late Miocene.

6.5. Oligocene – Miocene turbidite system over Beira High

By the end of Eocene, planation of the African topography (Partridge and Maud, 1987) deprived the African rivers of sediments. The base Oligocene – Top Eocene (Top MBSU-4) reflector unconformity relates to the global eustatic change in sea level (Figures 3-7). The delta forest retreated landwards by almost 100 km during this time exposing the shelf in the Zambezi Delta Depression (ZDD) (De Buyl and Flores, 1986; Droz and Mougenot, 1987b). Significant amount of sediments on the shelf and the submarine terrace over Beira High were eroded by deep incising canyons and valleys in the Zambezi Delta Depression and transported to the mouth of the valley in the deeper basin. After the marine regression phase, sediment input was revived into the basin by the new African surface topography (Castelino et al., 2015; Partridge and Maud, 1987; Walford et al., 2005). Well-developed clinoforms at the prograding shelf edge (Figures 6.7-6.8) indicate the increase in sediment supply that outpaces the creation of new accommodation space. The chaotic and discontinuous character of sediment deposition and development of several channels indicates a high-energy environment on the shelf and the intermediate terrace. During the subsequent phase, a massive channel levee complex formed over Beira High (Figure 6.5-6.6; Phase 2) with a deep channel. We associate this change in depositional regime to the reactivation of the northwest - southeast oriented Inhaminga fault system during Middle-Miocene that cuts the older northwest –southeast Zambezi graben and temporarily diverted the sediment load of the Zambezi further south towards Beira along the Urema Graben (De Buyl and Flores, 1986; Flores, 1973). The activity in the channel ceased or reduced when the course of the Zambezi was later restored close to its present-day position. The channel was subsequently filled with well-strafied sediments of a low energy environment or suspended sediment load a different turbidite system.

6.6. Miocene – Pliocene/Pleistocene development of the Zambezi Channel system

From our profiles, it is difficult to speculate on the timing of the onset of the activity in the Zambezi Valley (Figure 6.1-6.3). However, further down the channel, Droz and Mougenot (1987) find the Serpa-Pinto Valley (Figure 6.1) deposits underlie the Zambezi Channel deposits. This would constrain the age of Zambezi valley to around the middle

Miocene. This coincides with continued East African taphrogenesis onshore Mozambique and adoption of the Zambezi's present-day course. This suggests that the sediment load that was previously transported over Beira Channel-Levee system was subsequently diverted north along the shelf with littoral drifts before being flushed down the Zambezi canyons and valley and into the Zambezi Channel where it is deposited as levee deposits.

The chaotic sediments and sheeted drapes that fill the valley (Figure 6.3) suggest a reduced activity in the valley. This supports the argument by Droz and Mougenot (1987) further south who interpret missing Pliocene sediments on the levee (Kolla et al., 1980) to the reduced activity in the channel. They presume that the missing sediments have not been eroded by deep-water currents implying the channel ceased to supply sediment during the Pliocene. When submarine canyons are cut actively, they are repeated flushed by sediment gravity flows and become a zone of sediment bypass. Canyon cutting ceases when it achieves stability through successive slumps (Coleman et al., 1983) or when the energy level decreases during lowstand wedge time. Slump deposits or fine pelagic and hemi-pelagic sediments gradually fill the canyons. On the contrary, the sedimentation rates in the basin have increased (Castelino et al., 2015; Walford et al., 2005), that is associated to continental uplift of magnitudes of almost 1000 m and the doubling of the Zambezi catchment area (Walford et al., 2005). The sediment supply to the head of the canyons at the shelf appears to have been cut off. The sediment deposits in the valley are most likely slump deposits related to stabilization of the system with only a small fraction of the sediment load discharged by the rivers being deposited.

6.7. Present-day source to sink pathway

Sedimentation rates in the Zambezi delta inferred from ischore maps show an increase in the sediment load of the Zambezi (Castelino et al., 2015; Walford et al., 2005). However, the pathways transporting sediments are still undetermined. The bathymetry contours on the shelf (Beiersdorf et al., 1980) show graben-like structures in the Zambezi Delta that are filled with Pliocene sediments. While significant amounts of the sediments are deposited on the shelf, it is suspected that sediments are transported to the Mozambique Fan via the re-excavated Chinde-Zambezi graben (Droz and Mougenot, 1987b) (Figure 6.9). The presence of Pliocene sediments lead Droz and Mougenot (1987) to suggest that this graben trapped the sediments and starved the Zambezi canyon that fed the Zambezi valley. Seismic profiles and new bathymetry show the presence of northwest-southeast oriented valleys originating close to the shelf and meander southwards east of Beira High. This supports the hypothesis of Droz and Mougenot (1987) that some of the sediments bypass the shelf and flow south directly into the Mozambique Channel. The valley meanders at the base of the slope where the gradient of the slope changes before entering the deeper basin west of Bassas da India and Europa Islands (Figure 6.9). Some of the sediments are transported further north along the narrow shelf with littoral drifts before entering the basin through a group of closely spaced canyons that incise the continental slope.

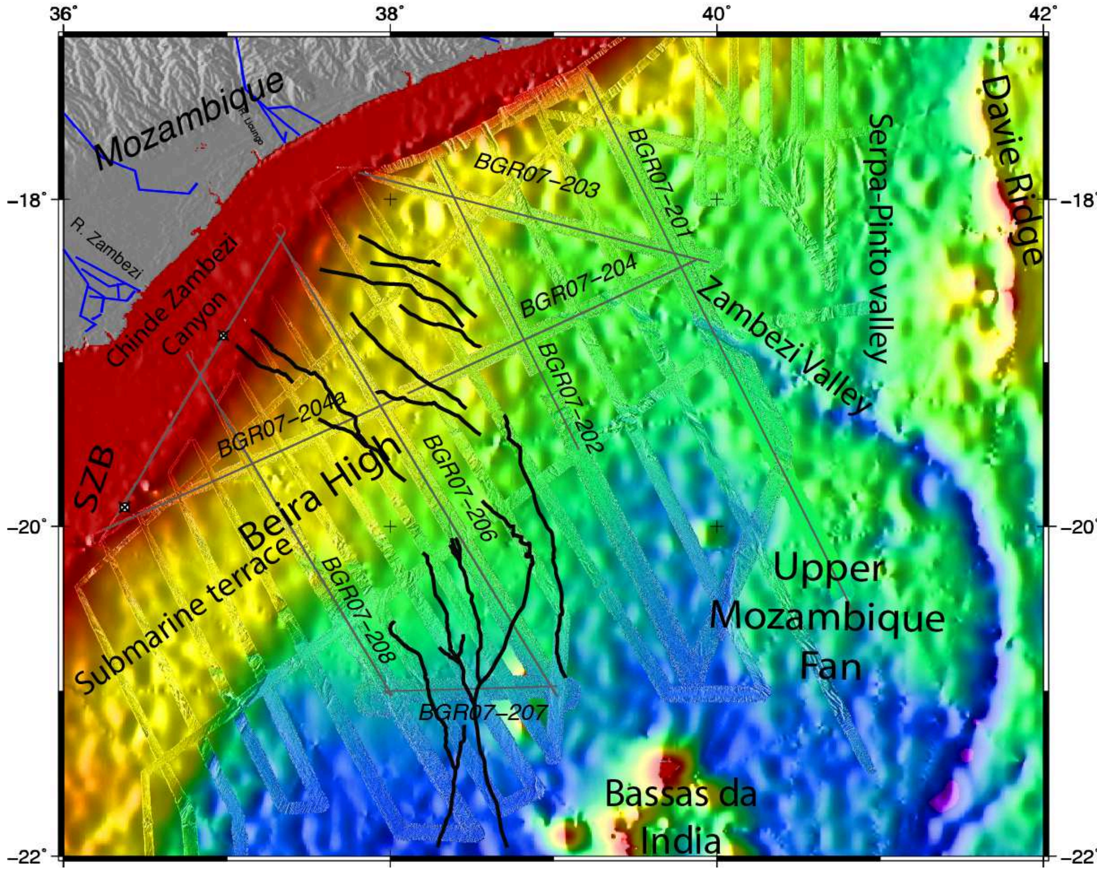


Figure 6.9: Submarine valleys at the base of the submarine terrace that provides pathways for the sediment load to directly bypass the shelf.

6.8. Conclusions

The development of the submarine fan in the Mozambique Basins in the Late Cretaceous makes it one of the oldest identified depositional systems. Onshore tectonic activity/uplift is the apparent mechanism and primary control for the development of the deep sea fan. Every event, tectonic uplift and associated sea level change has a significant impact on the sediment delivery pathways. The increase in sediment supply into the basin, which is also a consequence of tectonic activity, has a delayed impact on the development turbidite system.

The controls on two ancient turbidite systems in the basin that pre-dates the inactive Zambezi Valley identified by Droz and Mougenot (1987) hare described in this study and we also present some more evidences to the speculated present-day turbidite system connected to the Zambezi River. The development of these ancient systems shows two or more active phases controlled initially by tectonic activity and then later by sediment type and supply. From Late Cretaceous to Eocene, the Zambezi Fan first developed in response to onshore tectonic uplift. The early phase is associated to instantaneous response to local sea level fall. During the subsequent phase, the fan was fed by the increased sediment influx from the Zambezi River. The effect of bottom currents on the dispersal of the fan is very significant in comparison to other fans.

From Oligocene- to middle Miocene, the sediment supply migrated south over Zambezia-Sofala Bank. The early phase is related to the eustatic sea level change during mid-Oligocene when several canyons eroded the shelf and submarine terraces. This was followed by formation of valleys and a prograding shelf with a steady supply of sediments from the Zambezi Delta and a rising sea level. Reactivation of the Inhaminga fault system during middle Miocene changed the course of the Zambezi. This resulted in the development of the channel-Levee system on the intermediate terrace over Beira High.

Since mid Miocene, the taphrogenesis along the Urema graben redirected significant amounts of sediments northwards where they bypassed the shelf and flushed down the Zambezi Canyon-valley system into the basin. The sediment supply to the head of the canyon ceased as a result of continued tectonic activity. Presently, the sediment load is trapped in the Chinde-Zambezi graben in the Zambezi Delta and is transported into the basin by valleys that extend over the submarine terrace between Zambezi Valley, Beira High and Bassas da India. Another fraction of the sediment load is carried further north by littoral drifts and enter the basin through closely spaced canyons on the slope.

6.9. Acknowledgement

We are grateful to the contributions of Graeme Eagles in improving the content and for the English corrections.

Chapter 7: Conclusions and summary

The new Geophysical datasets acquired during the MoBaMaSis Project provide a new insight into the sedimentation and evolution of the Mozambique Basin. This dissertation describes the acquisition, processing and interpretation of 2200 km of MCS and bathymetry data to identify important sediment features that has shaped the structure of the basin. Several new structures have been identified in this new dataset that combined with regional stratigraphy compiled from previous studies and extrapolated into the basin provide important constraints in the development of the basin. This chapter focuses on the highlights of the new discoveries in the study area that are described in the scientific contributions to peer-reviewed journals.

Consistent with continental breakup and seafloor spreading models, the oceanic basement of the Mozambique Basin subsided rapidly until Cretaceous times. Our estimates indicate up to 4 km of subsidence during the Mesozoic. Thermal subsidence accounts for the majority of the subsidence with sediment loading accounting for the rest. The absence of any major sediment depositional features in Jurassic and Lower Cretaceous strata indicates restricted oceanic circulation within the basin, resulting in occasional euxinic conditions and continuous aggradation of fluvial sediments. The lower sedimentary sequences have a velocity of 4.5 km/s; such high velocities are otherwise uncommon in sediments, but are widespread along the East African Margin. A low velocity layer of 3.7 km/s with a thickness of approximately 200 ms (TWT) in the northern part of the basin is interpreted as undercompacted-overpressure shale.

The onset of bottom currents flowing in the north-south direction during the Late Cretaceous changed the conditions to a current swept basin. This bottom current originates as far north as the Somali Basin, but its southern extent is still undetermined. The influence of the bottom current waned during the Eocene and eventually ceased or was confined to the deeper basin within the channel.

The impact of major tectonic events along the East African margin is reflected in the sedimentation rates in the Mozambique Basin. A surge in sediment discharge by fluviatile systems is preceded by episodes of tectonic uplift of the African continent. The sedimentation rates show a decline after the Gondwana breakup. A surge in sediment influx is observed after tectonic uplift of Africa in Late Cretaceous times. The onset of this north-south bottom current resulted in the formation of a peculiar elongated submarine fan on the continental rise. This Late Cretaceous Mozambique Fan was the main conduit for sediment from the Zambezi River into the Mozambique Channel. The submarine fan was active until Eocene, after which it was starved of sediment due to reduced transport by the Zambezi River.

The development of the submarine fan in the Mozambique Basins in the Late Cretaceous makes it one of the oldest identified depositional systems. The onshore tectonic activity/uplift is the apparent mechanism and primary control for the early development of the deep sea fan. Each instance of tectonic uplift or eustatic sea level change has a significant impact on the short-term sediment delivery pathways. The increase in sediment supply in to the basin, which is also related to tectonic events, has a delayed impact on the development turbidite system.

Two additional ancient turbidite systems from the Zambezi River in addition to the one ancient recognized by Droz and Mougenot (1987) are identified in the basin. The ancient systems exhibit two or more active phases controlled by tectonic activity and sediment supply during its development. From Late Cretaceous to Eocene, the Zambezi Fan developed in response to tectonic activity onshore. The early phase is associated to instantaneous response to regional change in the relative sea level due to tectonic uplift. During the subsequent phase, the fan was fed by the increased sediment influx. The effect of bottom currents on the dispersal of the fan is very significant in comparison to other fans.

From Oligocene- to middle Miocene, the sediment supply shifted further south over Zambezia-Sofala Bank. The early phase is related to the eustatic sea level change during mid-Oligocene when several canyons eroded the shelf and submarine terraces and was followed by formation of valleys and prograding shelf. The development of Basin Floor Fans during the Miocene coincides with the beginning of uplift of Africa. This is followed by increased sediment influx in the basin. Reactivation of the Inhaminga fault system during middle Miocene temporarily diverted the course of the Zambezi south towards Beira, resulting in the development of the Channel-Levee system over Beira High.

Since the mid Miocene, the taphrogenesis along the Urema graben diverted significant amounts of sediments northwards where they bypassed the shelf and flushed down the Zambezi Canyon-valley system into the basin. The sediment supply to the head of the canyon ceased as a result of continued tectonic activity. This has lead to reduced activity within the valley and sediment infilling of the graben. The new bathymetry data supports the hypothesis that the sediment load is presently trapped in the Chinde-Zambezi graben in the Zambezi Delta and is transported into the basin by valleys that extend over the submarine terrace between Zambezi Valley, Beira High and Bassas da India.

For the first time, palaeobathymetry modelling of the Southwest Indian Ocean has been attempted using the backstripping technique. The palaeobathymetric illustrates the early phase of separation between Antarctica and Africa since 140 Ma. The evolution of the oceanic basement is clearly asymmetric. The first conclusive evidence of a regional positive bathymetric anomaly, measuring up to 1300 m, is revealed in the Mozambique Basin. Uplift of similar magnitude in neighbouring South Africa and Madagascar during Pliocene and later is widely attributed to dynamic support of the lithosphere by mantle convection. However, that mechanism cannot sufficiently account for the Mozambique Basin anomaly The anomaly is speculated to be caused by crustal underplating associated to the addition of excess melting and related to the passage of the basin over a region of warm mantle or hotspot.

Thermal subsidence is found to deviate from the Classic age-depth relationship. We attribute the deviation to the flexure of oceanic crust continent-ocean boundaries and possibly an expression of the physical and mechanical properties determined by the margin-type. The half- wavelength of the flexure is approximately 60-80 km with amplitude of up to 1500 m. This flexure has to be incorporated for models older than 100 Ma when the oceanic crust at the COTZ is younger than 70 Myr; otherwise thermal subsidence is overestimated. Furthermore, the thermal subsidence of isolated breakup-related topographic elevations/elevated crustal blocks like Beira High and around Gunnerus Ridge can be modelled with subsidence rates that mimic those of oceanic crust similar in age to the breakup.

Finally, the discovery of sedimentary features and palaeo-bathymetric model provides important constraints on palaeo-ocean circulation models in the Mozambique Channel. However, our knowledge of the evolution of the Mozambique Channel remains incomplete. Suggestions for future work are discussed in the next chapter.

Chapter 8: Outlook and future perspective

The Mozambique Basin is a prime example of a complex evolutionary region that has been poorly studied until now. My dissertation gives an overview of some major features and processes that highlights the complexity of the region. I have identified several remaining ambiguities in the tectonic and geologic evolution of the basin that may serve as a foundation for future studies on the basin.

The palaeo-bathymetry models are incomplete and several aspects of the model can be improved further. The modelling was done only for the oceanic crust along the Antarctic-Africa Corridor (AAC). Amongst the poorly constrained features are areas in the Zambezi Delta, Mozambique Flood plains, small and large crustal blocks, namely Mozambique Ridge; Astrid Ridge; Gunnerus Ridge; and Beira High and, regions abutting the oceanic crust. Although we elucidate the behaviour of these features, quantifying the relationship would improve our understanding of lithosphere dynamics.

The timing and process that resulted in the anomalous seafloor topography in the Mozambique Basin is undetermined. It assumes significance due to its areal extent. Presence of Bassas da India and Isle de Europa Islands suggest that it maybe a part of the volcanic chain that passes over a hotspot. However, it may also be a far-field expression of mantle activity around the basin. Additional geophysical data and analysis is needed to investigate in greater detail the crustal structure and its origin.

Another important discovery from the palaeobathymetric modelling is the deviation of the thermal subsidence of the oceanic crust from the classical age-depth model at continent ocean transition zones. A comparison at other passive margins around the world reveals that this behaviour is more of a norm rather than an exception. We speculate that this behaviour is related to the flexural properties of the crust that maybe related to type of margin or break-up. Future studies should focus on the relationship between the observed flexure and the margin evolution.

The Mesozoic sediments display unusually high velocity in the Mozambique Basin and along Eastern African margin. Local stratigraphy from onshore wells, show that these maybe continental red bed. It maybe worthwhile to investigate in-situ the composition of these sediments and verify whether the overlying thick layers of sediments or metamorphic effects on the structure are responsible for the high velocity.

Lack of additional geophysical data has precluded a detailed analysis of the present-day source to sink pathways in the basin. The third manuscript highlights the little information we have on the development of the Mozambique Fan. Along slope like Contourite Deposition Systems (CDS) and downslope processes like turbidity currents play a very important role on how the sediments are distributed in the basin. Future expeditions might be aimed to explore the impact of these processed on the marine sediment dispersal systems at different locations with high-resolution methods like sidescan sonar, Acoustic Doppler Current Profiles (ADCP) and sediment echosounder.

Acknowledgements

Firstly, I would like to thank Prof. Dr. Wilfried Jokat for giving me the opportunity to work on this project and also for all the support and facilities at the AWI. The discussions on scientific and not-so-scientific aspects have definitely been a motivation for me to work. Thanks to Prof. Dr. Katrin Huhn-Frehers for the interest in my work and the willingness to review my thesis.

A great part of my work would not possible without the help and support of Dr. Graeme Eagles to whom I owe the success of my publication. I am very grateful for all the intense and enlightening discussions we have had, for being very critical of the manuscripts and proof-reading all what I have written.

I am much obliged to the Alfred-Wegener-Institute and Polmar graduate school for the support and encouragement throughout my Ph.D. and especially all the training courses and events.

Many thanks to Florian Schmidt and Katharina Hochmuth for helping me with the impossible task of translating my abstract into German. Paul Gierz and Margaret Lindemann for proof-reading parts of my thesis.

Thanks to my officemate Christian Olaf Mueller (Digga) and Max Fischer for the very lively atmosphere in the office and all the brilliant new ideas for our fictional start-up company!

My colleagues and friends at the AWI and University of Bremen for their continued support, social distractions, the coffee machine, countless cakes, train rides, terrace gatherings and the feierabend beer.

Lastly, I must thank my family for encouraging me to finish my studies so far away from home.

Bibliography

Artemieva, I.M., Vinnik, L.P., 2016. Density structure of the cratonic mantle in Southern Africa: 1. Implications for dynamic topography. Gondwana Res. doi:10.1016/j.gr.2016.03.002

Bahr, D.B., Hutton, E.W.H., Syvitski, J.P.M., Pratson, L.F., 2001. Exponential approximations to compacted sediment porosity profiles. Comput. Geosci. 27, 691–700. doi:10.1016/S0098-3004(00)00140-0

Baldwin, B., Butler, C.O., 1985. Compaction curves. Am. Assoc. Pet. Geol. Bull. 69, 622–626.

Bassias, Y., 1992. Petrological and geochemical investigation of rocks from the Davie fracture zone (Mozambique Channel) and some tectonic implications. J. African Earth Sci. (and Middle East) 15, 321–339. doi:10.1016/0899-5362(92)90018-8

Beiersdorf, H., Kudrass, H.-R., von Stackelberg, U., 1980. Placer Deposits of limenite and Zircon on the Zambezi Shelf. Schweizerbart Science Publishers, Stuttgart, Germany.

Bouma, A.H., Normark, W.R., Barnes, N.E., 2012. Submarine fans and related turbidite systems. Springer Science & Business Media.

Burgess, S.D., Bowring, S.A., Fleming, T.H., Elliot, D.H., 2015. High-precision geochronology links the Ferrar large igneous province with early-Jurassic ocean anoxia and biotic crisis. Earth Planet. Sci. Lett. 415, 90–99. doi:10.1016/j.epsl.2015.01.037

Burke, K., 1996. The African Plate. South African J. Geol. 99, 341–409.

Castelino, J.A., Eagles, G., Jokat, W., 2016. Anomalous bathymetry and palaeobathymetric models of the Mozambique Basin and Riiser Larsen Sea. Earth Planet. Sci. Lett. 1–.

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

Cochran, J.R., 1988. Somali Basin, Chain Ridge, and origin of the Northern Somali Basin gravity and geoid low 93, 11985–12008. doi:10.1029/JB093iB12p15344

Coffin, M.F., 1992. The east African and Madagascar margins: Stratigraphy, structure and tectonics, in: First Indian Ocean Petroleum Seminar. pp. 325–343.

Coffin, M.F., Rabinowitz, P.D., 1987. Reconstruction of Madagascar and Africa: Evidence from the Davie Fracture zone and Western Somali basin. J. Geophys. Res. 92, 9385–9406. doi:10.1029/JB092iB09p09385

Coffin, M.F., Rabinowitz, P.D., Houtz, R.E., 1986. Crustal structure in the Western Somali Basin. Geophy 2, 331–369.

Coleman, J.M., Prior, D.B., Lindsay, J.F., 1983. Deltaic influences on shelfedge instability processes., The shelfb. ed.

Cox, K.G., 1992. Karoo igneous activity, and the early stages of the break-up of Gondwanaland. Geol. Soc. London, Spec. Publ. 68, 137–148. doi:10.1144/GSL.SP.1992.068.01.09

Crosby, A.G., McKenzie, D., Sclater, J.G., 2006. The relationship between depth, age and gravity in the oceans. Geophys. J. Int. 166, 553–573. doi:10.1111/j.1365-246X.2006.03015.x

Curray, J.R., Emmel, F.J., Moore, D.G., 2002. The Bengal Fan: morphology, geometry, stratigraphy, history and processes. Mar. Pet. Geol. 19, 1191–1223. doi:10.1016/S0264-8172(03)00035-7

De Buyl, M., Flores, G., 1986. The Southern Mozambique Basin: The Most Promising Hydrocarbon Province Offshore East Africa. Am. Assoc. Geol. Bull. 68, 399–425.

Droz, L., Mougenot, D., 1987a. Mozambique upper fan: origin of depositional units. AAPG Bullletin 71, 1355–1365.

Droz, L., Mougenot, D., 1987b. Mozambique Upper Fan : Origin of Depositional Units. Am. Assoc. Pet. Geol. Bull. 71, 1355–1365.

Duncan, R. a., Hooper, P.R., Rehacek, J., Marsh, J.S., Duncan, a. R., 1997. The timing and duration of the Karoo igneous event, southern Gondwana. J. Geophys. Res. 102, 18127. doi:10.1029/97JB00972

Eagles, G., König, M., 2008. A model of plate kinematics in Gondwana breakup. Geophys. J. Int. 173, 703–717. doi:10.1111/j.1365-246X.2008.03753.x

Eagles, G., Pérez-Diaz, L., Scarselli, N., 2015. Getting over Continent Ocean boundaries. Earth Sci. Rev. 151, 1–56. doi:10.1016/j.earscirev.2015.10.009

Ehlers, B.-M., Jokat, W., 2013. Paleo-bathymetry of the northern North Atlantic and consequences for the opening of the Fram Strait. Mar. Geophys. Res. 34, 25–43. doi:10.1007/s11001-013-9165-9

Flores, G., 1973. The Cretaceous and Tertiary sedimentary basins of Mozambique and Zululand. Sediment. basins African coasts 2, 81–111.

Flores, G., 1984. The SE Africa triple junction and the drift of Madagascar. J. Pet. Geol. 7, 403–418. doi:10.1111/j.1747-5457.1984.tb00885.x

Foerster, R., 1975. The Geological history of the sedimentary basin of Southern Mozambique, and some aspects of the origin of the Mozambique channel. Paleogeography, Paleoclimatology, Paleoecol. 17, 267–287.

Gaina, C., Torsvik, T.H., van Hinsbergen, D.J.J., Medvedev, S., Werner, S.C., Labails, C., 2013. The African Plate: A history of oceanic crust accretion and subduction since the Jurassic. Tectonophysics 604, 4–25. doi:10.1016/j.tecto.2013.05.037

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

Gohl, K., Uenzelmann-Neben, G., 2001. The crustal role of the Agulhas Plateau, southwest Indian Ocean: evidence from seismic profiling. Geophys. J. Int. 144, 632–646. doi:10.1046/j.1365-246x.2001.01368.x

Gohl, K., Uenzelmann-Neben, G., Grobys, N., 2011. Growth and Dispersal of a Southeast African Large Igneous Province. South African J. Geol. 114, 379–386. doi:10.2113/gssajg.114.3-4.379

Gradstein, F.M., Ogg, J.G., Schmitz, M., Ogg, G., 2012. The Geologic Timescale, The Geologic Time Scale 2012 2-Volume Set.

Gurnis, M., Mitrovica, J.X., Ritsema, J., van Heijst, H.-J., 2000. Constraining mantle density structure using geological evidence of surface uplift rates: The case of the African Superplume. Geochemistry, Geophys. Geosystems 1. doi:10.1029/1999GC000035

Haq, B.U., Al-Qahtani, A.M., 2005. Phanerozoic cycles of sea-level change on the Arabian platform. GeoArabia 10, 127–160.

Hartnady, C.J.H., 1985. Uplift, faulting, seismicity, thermal spring and possible incipient volcanic activity in the Lesotho-Natal Region, SE Africa: The Quathlamba Hotspot Hypothesis. Tectonics 4, 371–377.

doi:10.1029/TC004i004p00371

Huang, X., Gohl, K., Jokat, W., 2014. Variability in Cenozoic sedimentation and paleo-water depths of the Weddell Sea basin related to pre-glacial and glacial conditions of Antarctica. Glob. Planet. Change 118, 25–41. doi:10.1016/j.gloplacha.2014.03.010

Huang, Z., Gradstein, F.M., 1990. Depth-porosity relationship from deep sea sediments. Sci. Drill. 1, 157–162.

Jokat, W., 2014. The expedition of the Research Vessel “Sonne” to the Mozambique Basin in 2014 (SO230). Reports Polar Mar. Reseach 676.

Jokat, W., Boebel, T., König, M., Meyer, U., 2003. Timing and geometry of early Gondwana breakup. J. Geophys. Res. 108, 2428. doi:10.1029/2002JB001802

Kamen-Kaye, M., 1982. Mozambique-Madagascar geosyncline,!: Deposition and architecture. J. Pet. Geol. 5, 3–30. doi:10.1111/j.1747-5457.1982.tb00558.x

Kolla, V., Kostecki, J.A., Henderson, L., Hess, L., 1980. Morphology and Quaternary sedimentation of the Mozambique Fan and environs, southwestern Indian Ocean. Sedimentology 27, 357–378. doi:-

König, M., Jokat, W., 2006. The Mesozoic breakup of the Weddell Sea. J. Geophys. Res. 111, B12102. doi:10.1029/2005JB004035

König, M., Jokat, W., 2010. Advanced insights into magmatism and volcanism of the Mozambique Ridge and Mozambique Basin in the view of new potential field data. Geophys. J. Int. 180, 158–180. doi:10.1111/j.1365-246X.2009.04433.x

Korenaga, T., Korenaga, J., 2008. Subsidence of normal oceanic lithosphere, apparent thermal expansivity, and seafloor flattening. Earth Planet. Sci. Lett. 268, 41–51. doi:10.1016/j.epsl.2007.12.022

Kuvaas, B., Kristoffersen, Y., Leitchenkov, G., Guseva, J., Gandjukhin, V., 2004. Seismic expression of glaciomarine deposits in the eastern Riiser Larsen Sea, Antarctica. Mar. Geol. 207, 1–15. doi:10.1016/j.margeo.2004.04.004

Leinweber, V.T., Jokat, W., 2011. Is there continental crust underneath the northern Natal Valley and the Mozambique Coastal Plains? Geophys. Res. Lett. 38, n/a–n/a. doi:10.1029/2011GL047659

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

Leinweber, V.T., Klingelhoefer, F., Neben, S., Reichert, C., Aslanian, D., Matias, L., Heyde, I., Schreckenberger, B., Jokat, W., 2013. The crustal structure of the Central Mozambique continental margin — Wide-angle seismic, gravity and magnetic study in the Mozambique Channel, Eastern Africa. Tectonophysics 599, 170–196. doi:10.1016/j.tecto.2013.04.015

Leitchenkov, G., Guseva, J., Gandyukhin, V., Grikurov, G., Kristoffersen, Y., Sand, M., Golynsky, A., Aleshkova, N., 2008. Crustal structure and tectonic provinces of the Riiser-Larsen Sea area (East Antarctica): results of geophysical studies. Mar. Geophys. Res. 29, 135–158. doi:10.1007/s11001-008-9051-z

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

Miller, K.G., Fairbanks, R.G., 1983. Evidence for Oligocene–Middle Miocene abyssal circulation changes in the western North Atlantic. Nature 306, 250–253. doi:10.1038/306250a0

Mueller, C.O., Jokat, W., Schreckenberger, B., 2016. The crustal structure of Beira High, central Mozambique - Combined investigation of wide-angle seismic and potential field data. Tectonophysics. doi:10.1016/j.tecto.2016.06.028

Müller, R.D., Sdrolias, M., Gaina, C., Roest, W.R., 2008a. Age, spreading rates, and spreading asymmetry of the world's ocean crust. Geochemistry, Geophys. Geosystems 9, 1–19. doi:10.1029/2007GC001743

Müller, R.D., Sdrolias, M., Gaina, C., Steinberger, B., Heine, C., 2008b. Long-Term Sea-Level Fluctuations. Science 319, 1357–1363.

Mutti, E., Normark, W.R., 1991. Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems, in: Weimer, P., Link, M.H. (Eds.), . Springer New York, New York, NY, pp. 75–106. doi:10.1007/978-1-4684-8276-8_4

Nairn, A.E.M., Lerche, I., Iliffe, J.E., 1991. Geology, basin analysis, and hydrocarbon potential of Mozambique and the Mozambique Channel. Earth-Science Rev. 30, 81–123. doi:10.1016/0012-8252(91)90014-7

Nelson, C.H., Kulm, L.D., 1973. Submarine fans and channels. Soc. Econ. Paleotologists abd Mineral. Short Course 39–78.

Nugent, C., 1990. The Zambezi River: tectonism, climatic change and drainage evolution. Palaeogeogr. Palaeoclimatol. Palaeoecol. 78, 55–69. doi:10.1016/0031-0182(90)90204-K

Parsons, B., Sclater, J.G., 1977. An analysis of the variation of ocean floor bathymetry and heat flow with age. J. Geophys. Res. doi:10.1029/JB082i005p00803

Partridge, T.C., 1998. Of diamonds, dinosaurs and diastrophism; 150 million years of landscape evolution in southern Africa. South African J. Geol. 101 , 167–184.

Partridge, T.C., Maud, R.R., 1987. Geomorphic evolution of souther Africa since the Mesozoic. South African J. Geol. 90, 179–208.

Pérez-Díaz, L., Eagles, G., 2014. Constraining South Atlantic growth with seafloor spreading data. Tectonics 33, 1848–1873. doi:10.1002/2014TC003644

Rabinowitz, P.D., Coffin, M.F., Falvey, D., 1983. The separation of Madagascar and Africa. Science 220, 67–9. doi:10.1126/science.220.4592.67

Rebesco, M., Hernández-Molina, F.J., Van Rooij, D., Wåhlin, A., 2014. Contourites and associated sediments controlled by deep-water circulation processes: State-of-the-art and future considerations. Mar. Geol. 352, 111–154. doi:10.1016/j.margeo.2014.03.011

Reeves, C. V., 2000. The geophysical mapping of Mesozoic dyke swarms in southern Africa and their origin in the disruption of Gondwana. J. African Earth Sci. 30, 499–513. doi:10.1016/S0899-5362(00)00035-X

Reeves, C. V., de Wit, M.J., 2000. Making ends meet in Gondwana: retracing the transforms of the Indian Ocean and reconnecting continental shear zones. Terra Nov. 12, 272–280. doi:10.1046/j.1365-3121.2000.00309.x

Reeves, C. V., Sahu, B.K., de Wit, M.J., 2002. A re-examination of the paleo-position of Africa's eastern neighbours in Gondwana. J. African Earth Sci. 34, 101–108. doi:10.1016/S0899-5362(02)00011-8

Reichert, C., 2007. Cruise Report: MoBaMaSis-BGR07.

Roberts, G.G., Paul, J.D., White, N., Winterbourne, J., 2012. Temporal and spatial evolution of dynamic support from river profiles: A framework for Madagascar. Geochemistry, Geophys. Geosystems 13, 1–23. doi:10.1029/2012GC004040

Roberts, G.G., White, N., 2010. Estimating uplift rate histories from river profiles using African examples. J. Geophys. Res. Solid Earth 115, 1–24.

doi:10.1029/2009JB006692

Salazar, M.U., Baker, D., Malcolm, F., Kornpihl, D., Tekena, W., 2013. Frontier exploration offshore the Zambezi Delta, Mozambique. First Break 31, 135–144.

Salman, G., Abdula, I., 1995. Development of the Mozambique and Ruvuma sedimentary basins, offshore Mozambique. Sediment. Geol. 0738, 7–41.

Schlüter, P., Uenzelmann-Neben, G., 2008. Indications for bottom current activity since Eocene times: The climate and ocean gateway archive of the Transkei Basin, South Africa. Glob. Planet. Change 60, 416–428. doi:10.1016/j.gloplacha.2007.07.002

Sclater, J.G., Christie, P.A.F., 1980. Continental stretching: An explanation of the post-mid-cretaceous subsidence of the central North Sea basin. J. Geophys. Res. Solid Earth 85, 3711–3739.

Sleep, N.H., 1971. Thermal Effects of the Formation of Atlantic Continental Margins by Continental Break up. Geophys. J. Int. 24 , 325–350. doi:10.1111/j.1365-246X.1971.tb02182.x

Steckler, M.S., Watts, a. B., 1978. Subsidence of the Atlantic-type continental margin off New York. Earth Planet. Sci. Lett. 41, 1–13. doi:10.1016/0012-821X(78)90036-5

Stein, C.A., Stein, S., 1992. A model for the global variation in oceanic depth and heat flow with lithospheric age. doi:10.1038/359123a0

Storey, M., Mahoney, J.J., Saunders, A.D., Duncan, R.A., Kelley, S.P., Coffin, M.F., 1995. Timing of Hot Spot-Related Volcanism and the Breakup of Madagascar and India. Science 267, 852–855.

Stow, D.A. V, Howell, D.G., Nelson, C.H., 1984. Sedimentary, tectonic, and sea-level controls on submarine fan and slope-apron turbidite systems. Geo-Marine Lett. 3, 57–64. doi:10.1007/BF02462448

Stow, D.A. V, Howell, D.G., Nelson, C.H., 1985. Sedimentary, Tectonic, and Sea-Level Controls, in: Bouma, A.H., Normark, W.R., Barnes, N.E. (Eds.), . Springer New York, New York, NY, pp. 15–22. doi:10.1007/978-1-4612-5114-9_4

Thomas, D.S.G., Shaw, P.A., 1988. Late Cainozoic drainage evolution in the Zambezi basin: Geomorphological evidence from the Kalahari rim. J. African Earth Sci. (and Middle East) 7, 611–618. doi:10.1016/0899-5362(88)90111-X

Torsvik, T.H., Tucker, R.D., Ashwal, L.D., Eide, E.A., Rakotosolofo, N.A., De Wit, M.J.,

1998. Late Cretaceous magmatism in Madagascar: Palaeomagnetic evidence for a stationary Marion hotspot. Earth Planet. Sci. Lett. 164, 221–232. doi:10.1016/S0012-821X(98)00206-4

Tucholke, B.E., Carpenter, G.B., 1977. Sediment distribution and Cenozoic sedimentation patterns on the Agulhas Plateau. Bull. Geol. Soc. Am. 88, 1337–1346. doi:10.1130/0016-7606(1977)88<1337:SDACSP>2.0.CO;2

Turgeon, S.C., Creaser, R. a., 2008. Cretaceous oceanic anoxic event 2 triggered by a massive magmatic episode. Nature 454, 323–326. doi:10.1038/nature07076

Upadhyay, S.K., 2004. No Title, in: Seismic Reflection Processing: With Special Reference to Anisotropy. Springer Science & Business Media.

Walford, H., White, N., Sydow, J., 2005. Solid sediment load history of the Zambezi Delta. Earth Planet. Sci. Lett. 238, 49–63. doi:10.1016/j.epsl.2005.07.014

Watts, A.B., 2001. Gravity anomalies, flexure and crustal structure at the Mozambique rifted margin. Mar. Pet. Geol. 18, 445–455. doi:10.1016/S0264-8172(00)00079-9

Watts, A.B., Ryan, W.B.F., 1976. Flexure of the lithosphere and continental margin basins. Tectonophysics 36, 25–44. doi:10.1016/0040-1951(76)90004-4

Weimer, P., Link, M.H., 1991. Seismic Facies and Sedimentary Processes of Submarine Fans and Turbidite Systems, in: Weimer, P., Link, M.H. (Eds.), . Springer New York, New York, NY, pp. 3–7. doi:10.1007/978-1-4684-8276-8_1

Wessel, P., Smith, W.H.F., Scharroo, R., Luis, J., Wobbe, F., 2013. Generic Mapping Tools: Improved Version Released. Eos, Trans. Am. Geophys. Union 94, 409–410. doi:10.1002/2013EO450001

Whittaker, J.M., Goncharov, A., Williams, S.E., Müller, R.D., Leitchenkov, G., 2013. Global sediment thickness data set updated for the Australian-Antarctic Southern Ocean. Geochemistry, Geophys. Geosystems 14, 3297–3305. doi:10.1002/ggge.20181

Wold, C.N., 1995. Palaeobathymetric reconstruction on a gridded database: the northern North Atlantic and southern Greenland-Iceland-Norwegian sea. Geol. Soc. London, Spec. Publ. 90, 271–302. doi:10.1144/GSL.SP.1995.090.01.17

Appendix

A. Structure for input file for BalPal v0.9

```
CELL_CENTER     = 36.2 -19.2            #Midpoint of the grid cell
DEPTH_UNITS     = METERS                #metric system
ELEVATION       = 0                     #geoid elevation
WATER_DEPTH     = 2783.1, SW            #Water depth and type (here: Salt water)
CRUST_TYPE      = OC                    #Crust type
CRUST_AGE       = 12.023                #age of crust (thermal age)
TECT_PLATE      = AFR                   #Plate
TOTAL_SED_THICK = 817                   #Sediment thickness

TOP_AGE         = 0.0                   #Age of top layer (seafloor)
LAYER           = 1                     #Layer number
LITHOLOGY       = SJ                    #Lithology
STRAT_AGE_BASE  = -235, 3               #depth of layer relative to seafloor, age
LAYER           = 2                     #Layer number
LITHOLOGY       = SJ                    #Lithology
STRAT_AGE_BASE  = -375, 5               #depth of layer relative to seafloor, age
LAYER           = 3                     #Layer number
LITHOLOGY       = SS                    #Lithology
BOT_AGE         = -817, 12.0            #depth of bottom layer relative to seafloor, age
```

B. Example of default parameter file

```
# Isostatic Parameters:

COMP_DEPTH      = 100000          # meters
REF_THICK_OC    = 6500            # meters
REF_AGE_OC      = 170             # Ma
DENSITY_SW      = 1027            # kg/m3
DENSITY_OC      = 2850            # kg/m3
DENSITY_CC      = 2750            # kg/m3
MAX_DENSITY_ASTH= 3400            # kg/m3

# Sediment Compaction:

LITHOLOGY      = SHALE
EQUATION       = EXPONENTIAL
TERM_A         = 0.63
TERM_B         = 0.571
DEPTH_UNIT     = KILOMETER
UPPER_LIMIT    = 0.0
LOWER_LIMIT    = 10.4

LITHOLOGY      = SILT
EQUATION       = EXPONENTIAL
TERM_A         = 0.803
TERM_B         = 0.795
DEPTH_UNIT     = KILOMETER
UPPER_LIMIT    = 0.0
LOWER_LIMIT    = 23.0

LITHOLOGY      = SANDST
EQUATION       = EXPONENTIAL
TERM_A         = 0.617
TERM_B         = 0.555
DEPTH_UNIT     = KILOMETER
```

```
UPPER_LIMIT     = 0.0
LOWER_LIMIT     = 23.0

LITHOLOGY       = LIMEST
EQUATION        = POWER-LAW
TERM_A          = 0.754
TERM_B          = 0.1575
DEPTH_UNIT      = KILOMETER
UPPER_LIMIT     = 0.001
LOWER_LIMIT     = 6.0

# Thermal Subsidence:

THERM_FUNCTION  = SQUARE-ROOT
COEFF_A         = 2600
COEFF_B         = 365
YOUNGER_LIMIT   = 0.0
OLDER_LIMIT     = 19.94

THERM_FUNCTION  = EXPONENTIAL
COEFF_A         = 5651
COEFF_B         = 2473
COEFF_C         = 0.0278
YOUNGER_LIMIT   = 19.94
OLDER_LIMIT     = 200.0
```