SAINT PETERSBURG STATE UNIVERSITY / HAMBURG UNIVERSITY

East Antarctic Volcanic Margin: Crustal Structure and Tectonic Evolution

Master Thesis

Master Program for Polar and Marine Sciences POMOR

Author: Tatiana Sitnikova

Supervisors: Dr German L. Leichenkov
Dr Sascha Brune

Saint Petersburg/ Hamburg 2017

Scientific advisors:

1. Dr German Leitchenkov, Saint Petersburg State University and All-Russian Research Institute of Geology and Mineral Resources of the World Ocean FSUE "VNIIOkeangeologia named after I.S. Gramberg", Russia
2. Dr Sascha Brune, Department of Geodynamic Modelling , Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Germany

TABLE OF CONTENT

Abstract

Volcanic passive margins are formed where continents breakup causing flood volcanism during prerift and/or synrift stages of the continental separation. The significant magmatism are caused by the rising of the mantle plume which had penetrated the lithosphere of central Gondwana.

The early stage of Gondwana break-up is marked by significant flood basalt volcanism in the Karoo (SE Africa) and WDML (East Antarctica) from the initial expression of a mantle plume around 179-162 MA.

This work is focused on the study of the crustal structure and evolution of East Antarctic volcanic continental margin. It aims to generalize the knowledge on East Antarctica volcanic passive margins, and to characterize crustal architecture of the East Antarctic volcanic margin in terms of volcanostratigraphy and to compare it with the existing models.

This study will integrate different available data, including published articles, books, and seismic surveys acquired by PMGRE expeditions within 2011-2013.

Seismic data collected on the East Antarctic margin (in the eastern Weddell Sea and Lazarev Sea) show typical characteristic of volcanic margins. Following volcanostratigraphy concepts , the main volcanic facies (Outer SDR, Outer High, Inner SDR) were identified, mapped and analyzed. An attempt to reconstruct conjugate margins which were formed as a result of Gondwana break-up. The crustal transects obtained in the current study outlines the crustal structure of the central Lazarev Sea and Falkland Plateau and the eastern part of the Wedddell Sea and Central Mozambique Ridge accordingly.

Differences in the estimation of the age formation of Explora wedge (Middle Jurassic) and the East Weddell Sea crust based on magnetic anomalies(Late Jurassic) can be explained by the changes in strain localization which controlled by in depth magma distribution and causing the shift in the axis of the spreading. Similarly to North and South Atlantic excess magmatism at rifted margins , rifting in the East Antarctica probably occurred with the excess magmatism while opening has happened from the Risser-Larsen to the Weddell Sea .

Аннотация

Вулканические окраины образуются в местах раскола континентов и характеризуются значительным уровнем вулканизма. Обильный магматизм вызван подъемом мантийного плюма, который внедрился под литосферу центральной Гондваны. Ранняя фаза раскола Гондваны обозначается вулканизмом в районе провинции Кару (Южная Африка) и Западной Земли Королевы Мод (Восточная Антарктида) с первоначальными проявлениями мантийного плюма в период 179- 162 млн. лет назад.

Эта работа сосредоточена на изучении структуры земной коры и эволюции континентальной окраины Восточной Антарктики. Она направлена на обобщение знаний о вулканической окраины Восточной Антарктики и на описание строения земной коры вулканической окраины данного региона в рамках концепции вулканостратиграфии, а также сравнения результатов с существующими моделями

Данное исследование основано на использовании возможных доступных данных, включая опубликованные статьи, книги и сейсмические исследования, полученные экспедициями ПМГРЭ в течение 2011-2013 гг. Сейсмические данные, полученный на западе Восточной Антарктики (в восточном море Уэдделла и в Лазаревом море, показывают наличие типичных для вулканических окраин характеристик. Следуя концепции и вулканостратиграфии, основные вулканические фации были определены (Внешнее Поднятие, Внутренний Клин, Внешный Клин).

Предпринята попытка восстановить сопряженные вулканические окраины, сформированные в результате раскола Гондваны. Полученные разрезы показывают структуру коры центральной части Моря Лазарева и Фолклэндского плато, а также восточной части моря Уэдделла и центральной части Мозамбикского Хребта. Различия в оценке возраста формирования вулканического комплекса «Эксплора» (средняя юра) и коры восточной части моря Уэддэлла (поздняя юра) может объясняться изменением осевых деформаций, которые контролируются глубинным распределением магматического материала и могут вызвать в последствии смещение оси спрединга. Избыточный магматизм на вулканических окраинах Северной и Южной Атлантики происходил в условиях, сходных с рифтингом Восточной Антарктиды, где направления раскрытия происходило от моря Рисер-Ларсена к морю Уэделла.

List of abbreviations

GEBCO- General Bathymetric Chart of the Oceans

EWS- Eastern Weddell Sea

WDML- Western Dronning Maud Land

QML- Queen Maud Land

PMGRE- Polar Marine Geosurvey Expedition

AWI- Alfred Wegener Institute

RAE- Russian Antarctic Expedition

MCS- Multi Channel Seismic

LIP- Large Igneous Provinces

VPM- Volcanic Passive Margins

SPM- Sedimentary Passive Margins

SDR- Seaward Dipping Reflectors

1 Introduction

1.1 Location

East Antarctic volcanic margin is located off Dronning Maud Land; it borders the Weddell Sea, the Lazarev Sea and the Riiser- Larsen Sea between 30°W and 20°E, and forms part of the more than 2500-km long passive continental margin of East Antarctica (Jokat et al, 2005) and it includes following structural units of the volcanic origin: Explora Wedge, Polarstern Bank, Maud Rise, Maud Bank, Astrid Ridge, Gunnerus Ridge, Kainanmaru Bank. (Figure 1.1).

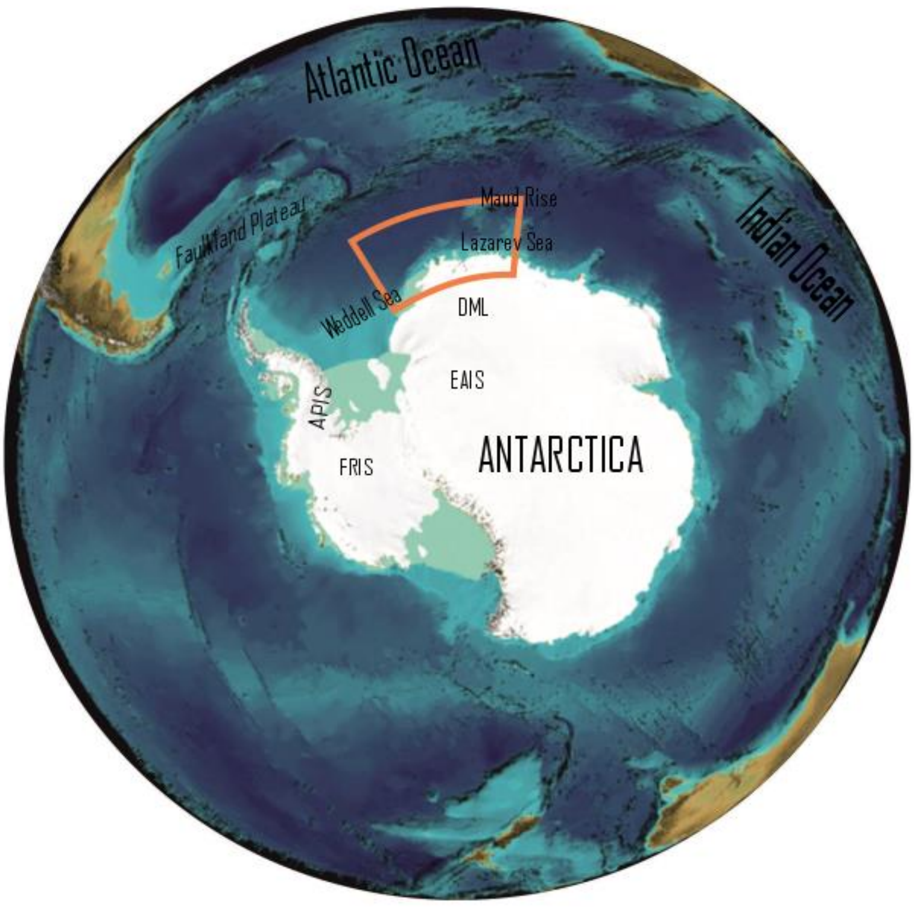

Figure 1.1 Overview map of the Antarctica. *It shows the location of the field work (red figure on the left); the shelf bathymetry, extent of ice shelves (grey), and the ice-sheet surface elevation. APIS: Antarctic Peninsula Ice Sheet; EAIS: East Antarctic Ice Sheet; FRIS: Filchner-Ronne Ice Shelf; DML: Dronning Maud Land (GEBCO bathymetry map, modified)*

1.2 Background and Objectives

The understanding of the origin of passive volcanic margins and the processes of their formation and development are of a crucial importance both for geology and geodynamics.

The current scientific themes are: 1) the structure of volcanic margins; 2) character of rifted continental crust reworking (modification) during magmatic emplacement; 3) geodynamic premises and models for volcanic margins intrusions; 4) position of continent- ocean boundary on the volcanic margins

This work is focused on the study of the crustal structure and evolution of East Antarctic volcanic continental margin (Hinz & Krauze, 1982, White & McKenzie, 1989). There are numerous studies that discuss the tectonic evolution of this area and describe East Antarcic volcanic margin origin (e.g. Hinz & Krauze, 1982; Leichenkov et al, 1994; Jokat et al., 2003; Konig & Jokat, 2006).

1. According to Hinz & Krauze, 1982, the dominating crustal feature of the eastern Weddell Sea is thick and voluminous volcanic sequence named "Explora Wedge", which was erupted on stretched continental crust during the late rift phase around the end of Mid- Jurassic time.

2. Leitchenkov et al, 1994 suggested that the near shore West Dronning Maud Land crustal densities, which are higher than normal, are caused by massive mafic plutons emplaced at different depths near to the continent- ocean transition.

3. Plate-kinematic reconstructions by Jokat et al. (2003) and König and Jokat (2006) show that southeast Africa was conjugate to the DML margin from just east of the Explora Escarpment to the Gunnerus Ridge.

The concept of seismic volcanostratigraphy to analize volcanic deposits imaged on seismic reflection data was developed by Planke et al, 2000.
However, no published study has specifically characterized the East Antarctic volcanic margin stratigraphy and this characterization will be offered in the current master thesis. The aims of this study are:

- To generalize the knowledge on East Antarctica volcanic passive margins;
- To compare volcanic margins development, architecture and to discuss the peculiarities and implications of their development in different regions;
- To review published conjugated margins models of South and North Atlantic region and to define possible conjugated margins of East Antarctica;
- To characterize crustal architecture of the East Antarctic volcanic margin in terms of volcanostratigraphy and to compare it with the existing models;
- To develop tectonic structure of the East Antarctic volcanic margin.

This study integrates different available data, including published articles, books, and seismic surveys acquired by PMGRE expeditions within 2011-2013.

2 Current Geological Knowledge

2.1 Regional settings of the study area

“The Weddell Sea is the deep embayment of the Antarctic coastline that forms the southernmost tip of the Atlantic Ocean. Centering at about 73° S, 45° W, the Weddell Sea is bounded on the west by the Antarctic Peninsula of West Antarctica, on the east by Coats Land of East Antarctica, and on the extreme south by frontal barriers of the Filchner and Ronne ice shelves. It has an area of about 2,800,000 square km”. (Encyclopedia Britannica).

The closest (to the Weddell Sea) scientific stations are the German station Neumayer-III, located in the Atka Bay on the Ekstrom Ice Shelf, and the South African SANAE IV station, located on the coast of Queen Maud Land on the Fimbul ice shelf (Figure 2.1).

In the western part of the Lazarev Sea it has a boundary with the Weddell Sea, and in the east the Astrid Ridge is separating it from the Riser-Larsen. Astrid Ridge is a bathymetrical high structure of approximately 400 km long and 90 km wide.

The closest (to the Lazarev Sea) scientific stations are and the Russian station Novolazarevskaya located in the region of the Schirmacher Oasis; the South African station Sanae, located on the coast of Dronning Maud Land on the Fimbul Ice Shelf and the Indian station of Meitri.

Bathymetry. The shelf of both the eastern Weddell Sea and the Lazarev Sea is almost completely hidden beneath the glaciers of Queen Maud Land. The width of the outer ice-free shelf does not exceed 10-40 km. The continental slope in the study area extends to the depths of 4000-4300 m at a width of 100-200 km. Between 3°E and 7°E the transition to abyssal (4500 m and more) depths is a steep (up to 18°) ledge of sublatitudinal strike. Between 9°W and 11°W, the morphostructure of the slope is complicated by a system of closely spaced canyons of the northwest strike. To the west of 10° W, the transition to the foot of continental slope represents a steep (up to 18°) ledge of northeasterly strike and is known in the literature as the Explora Escarpment.

The foot of the continental slope extends to 4500 m, with the smooth transition to the abyssal basin in the north. In the north of Lazarev Sea there is a rise in the seabed with depths of the sea of less than 4000 m, corresponding to the western margin of the underwater Maud Rise with its end in the north- western part of the

Lazarev Sea (Figure 1.1). To the south-east of it, in the central part of the central part of Lazarev Sea, a relatively small (100x75 km) bottom elevation is distinguished by an isobath of 3,500 m, for the sake of convenience, yet referred to as the "unnamed rise". (PMGRE report, 56th RAE)

2.2 History of geophysical research

A systematic geophysical study of this region has been started from the end of the 1970s. The first marine surveys were carried out by Norwegian Antarctic Research Expedition (NARE) in the 1976/77, 1978/79 seasons and by Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) in 1978/79 (Fossum et al. 1982; Hinz & Krauze 1982; Leichenkov 1996). A 48- channel, 2668-m-long analogue streamer and airgun array of 23.4 l total volume were used for seismic profiling (Hinz & Krauze 1982). About 3000 km of MCS lines were acquired during BGR work in the research area.

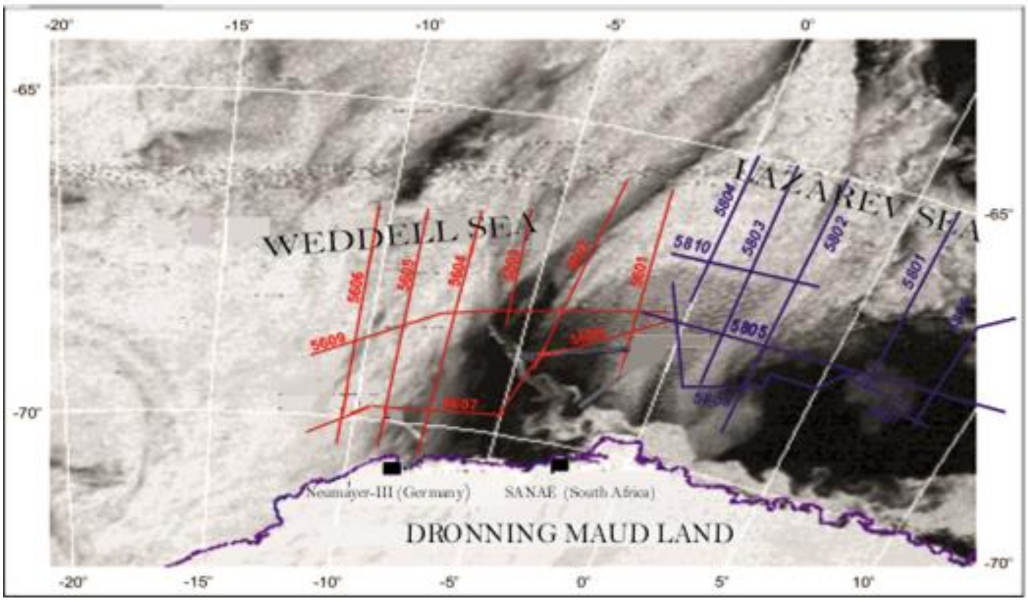

Figure 2.1 General overview of the Weddell and Lazarev Seas Basin, showing the network of MCS lines. *Red lines shows MCS line from 56th RAE, blue lines shows MCS lines from 58th RAE (modified, from the 56th & 58th reports data)*

During the 1981/82 season, the Japan National Oil Corporation together with Geological Survey of Japan (GSJ) aboard the Hakurei Maru vessel conducted geophysical research in the continental margin of the Queen Maud Land, around 1140 km of MCS data were obtained at the region of Weddell and Lazarev Seas. Seismic data were acquired using a 24-channel, 600-m-long streamer and two 7.4 l airguns.

In 1985/86, BGR conducted a geophysical survey aboard RV Polarstern, 770 km of seismic data were obtained in the study region using a 30-channel, 1500-m-long streamer and two 25.6 l airguns. In 1996 the study in this region were carried out BGR again aboard of Akademik Nemchinov vessel. 470 km of seimsic data in this region were obtained, using a 240-channels, 3000-m-long streamer and two 53.5 l airguns.

The results of seismic studies of foreign expeditions were sent to the Antarctic Seismic Data Library System (SDLS) and they are used in this master thesis.

The soviet marine seismic survey on the continental margin of the Queen Maud Land (in the sector 9°–17° W) was conducted during 34th Soviet Antarctic Expedition in 1989. 1200km of seismic data were acquired using a 24-channels, 1900-2300m-long streamer and two 7.5 l airguns.

In 1998 Polar Marine Geosurvey Expedition (PMGE) (under the 34-th Russian Antarctic Expedition, RAE) carried out marine geophysical survey in the Riiser-Larsen Sea but contains 750 km of MCS data from Lazarev Sea area. Seismic data were acquired using a 24-channels, 1750-long streamer and two 40 l airguns.

During the austral summer seasons 1996/1997 and 2001/2002, the ANTXIV/3 and ANT XVIII/2 expeditions aboard RV Polarstern were carried out to complement the existing data sets in the western Weddell Sea. Multichannel seismic (MCS) and seismic refraction data were acquired using a 96 channel 800m-long streamer with 24-litre pulser cluster. Detailed information on the survey is listed in Table 1.

In 2011 and 2012 PMGRE conducted geophysical studies in eastern Weddell and Lazarev Seas aboard RV Akademik Karpinsky in terms of 56th and 58th Russian Antarctic Expeditions (Figure 2.1). 3255 km of seismic data were obtained using a 352-channel digital streamer and two lines of airguns of 1420-2340 cub. in. (23-38 l) of total volume.

More details of the PMGRE seismic surveys will be given in the section 3.1 “Data and methodology” of the current master thesis.

Table 1. Summary of seismic surveys performed in Weddell Sea *(modified after Rogenhagen, 2000)*

Year	Institution	Ship	Total Survey, km
1977	NARE	Polarsirkel	1000
1978	BGR	SV Explora	5860
1979	NARE	Polarsirkel	1010
1983	JNOK	Hakurei Maru	1500
1985	NARE	Andenes	2600
1985	BAS	James Clark Ross	1940
1986	BGR	Polarstern	6260
1987	AWI	Polarstern	2800
1989	SAE	Akademik Fedorov	1200
1990	AWI	Polarstern	4100
1990	BGR	Polarstern	3000
1992	AWI	Polarstern	3900
1995	AWI	Polarstern	2600
1996	BGR	Akademik Nemchinov	3840
1996	AWI	Polar Queen	720
1997	AWI	Polarstern	4420
2002	AWI	Polarstern	2000
2011	PMGRE	Akademik Karpinsky	3235
2012	PMGRE	Akademik Karpinsky	3255
Total			**55240**

In 1988 and 1989 PMGRE conducted airborne geophysical (magnetic, radar and gravimetric) surveys in terms of 33rd and 34th Soviet Antarctic Expedition. 250 and 325 km data were obtained accordingly (Leitchenkov et al., 1994).

The aeromagnetic dataset in the area between 18 ºW and 8 ºE was supplemented by two helicopter surveys (~20,000 km) during the 1999/2000 season (Golynsky et al. 2007). This data were sent to the Antarctic Digital Magnetic Anomaly Project (ADMAP) database and it is available now.

A British Antarctic Survey acquired 15,500 line-km of aeromagnetic data during the 2001/02 Antarctic field season along a 1-km line spacing grid with the lines 8 km apart (Ferraccioli et al. 2005).

2.3 Geological and geophysical characteristics of the study area

2.3.1 Regional geology

The EWS interior regions demonstrate two main geomorphological provinces: a) the Dronning Maud Wilderness (WDML), which includes NE-SW-trending nunatak chains of more than 2000 m in height, and b) the predominantly flat Coats Land region, which is covered by ice sheet.

WDML is considered to consist of an ancient (archaean) cratonic terrain that borders the southeast by a polymetallomorphic terrain which represents either a recycled Archaean crystalline crust or a younger (about 1000Ma) supracrustal moving belt. The crystalline basement is covered in places with an Upper Precambrian flat volcanic and sedimentary layers and Late Paleozoic sequence. The thickness of the basalts is up to 2000m and their age range from 178 to 162 Ma at the top. Most of the dykes and felsic intrusions placed parallel to the fracture zones (Leitchenkov et al. 1996).

The complexes of metamorphic rocks of WDML show significant similarities to coeval rocks of southeastern Africa. The continental margin of the WDML, where PMGRE 56th RAE research was carried out, is the passive volcanic margin which extends for 1200 km from 30º W to 12º E (Figure 2.1).

Seismic refraction data indicate that the crustal structure of the WDML exhibits continental characteristics (Leitchenkov et al, 1996; Kudryavtsev et al, 1991). However, the outer (near shore) part of the region has the increased crustal density (0.1-0.2 gcc^{-1} higher than normal for a continental section) based on modeling of the long-wave length gravity with which is up to 140 mGal amplitude. This prominent feature is thought to be due to massive mafic plutons emplaced at different depth near to the continent- ocean transition (Leitchenkov et al, 1994).

The thickness of the sedimentary cover in the Lazarev Sea does not exceed 1.0-2.0 km, and the only seismic stratigraphic model was proposed by K. Hinz according to the results of the 1978 expedition (Hinz & Krause, 1982).

2.3.2 Structural and tectonic features of the Weddell Sea and the Lazarev Sea

Antarctica formed the central parts of the Late Proterozoic – Early Paleozoic supercontinents Rodinia and Gondwana. The early stage of Gondwana break-up is marked by the significant flood basalt volcanism in the Karoo (SE Africa) and WDML (East Antarctica) from the initial expression of a mantle plume around 179-162 MA (Leitchenkov et al. 1996).

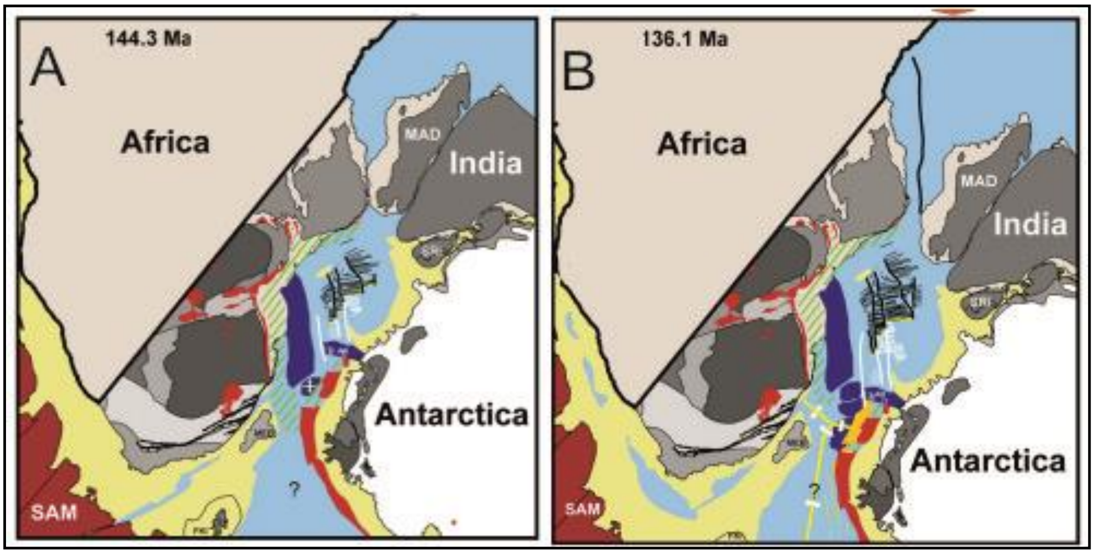

Figure 2.2 Kinematic model of Central Gondwana breakup A) 144. 3 MA B)136.1 MA *Regions marked with a green line pattern are considered as transitional crust. Spreading centres are marked with yellow lines. Thin black and white lines represent seafloor spreading anomalies. Thick black and white lines are fracture zones. Grey blocks are Precambrian and older crustal units. The beige areas are continental offshore crust. Light blue colours mark oceanic crust. Dark blue has been chosen to mark oceanic plateaus. The two SDRS-units of the Explora Wedge are painted in red and orange (modified after König and Jokat , 2006).*

The separation of the South American and Antarctic plates are caused the complete development of an east-west oriented spreading system facing the coast of western Dronning Maud Land by about 131 Ma (Jokat et al., 2003) . Seaward dipping reflector sequences (SDRs), seen in seismic records across the passive volcanic margins of South America and Africa indicate that this accompanied the beginning of seafloor spreading in the southern South Atlantic Ocean (Hinz et al., 2004). By about 118.0 Ma, the divergence of South America and Africa from Antarctica had given rise to a deep-water connection between the South Atlantic and the southwest India Ocean (Lawver et al., 1992).

As a result of South America drifting away from Antarctica at 147-122 Ma the first ocean crust was formed in the Weddell Sea (Figure 2.2) (König and Jokat, 2006). According to Leitchenkov et al. 1996, the eastern Weddell sea spreading is characterized by transtensional spreading, which occurred with the ultraslow velocities. Jokat et al., 1996, state that the continental crust in the southern Weddell Sea below the northern part of the Filchner-Ronne ice shelf characterized by lower thickness of approximately 20 km. It was noted by König and Jokat (2006) that the direction of the rifting which occurred from the east to west can be connected with the movement of the Antarctic Peninsula from East Antarctica at around 167 Ma while the early opening of the Weddell Sea happened at about 147 Ma in the a north- south direction.

The area of the Lazarev Sea was formed under the conditions of the stretching of the earth's crust of central Gondwana, in the Middle-Late Jurassic period, which ended in the division of the Indo-Australian-Antarctic and African-American plates.

Information about the age of the oceanic crust of the Lazarev Sea is very limited. After detailed aeromagnetic studies AWI 2009-2010. In the area of the Astrid Ridge, german specialists proposed a new model for the division of Africa and Antarctica (Leinweber & Jokat, 2012). According to this model (Figure 2.2), the area of the modern Lazarev Sea with the associated Mozambican basin of southeastern Africa at an early stage of the collapse of Godwana (between 160 and 140 million years) developed under the influence of active volcanism with the formation of volcanic structures. The greater part of the earth's crust of the Lazarev Sea, which existed at that time, is identified as a transitional (without explanation of the nature of such a crust) (Leinweber & Jokat, 2012).

About 145 million years ago, in the Lazarev Sea region (where the southern part of the Mozambican ridge was situated), a spreading ridge, parallel to the Astrid Ridge (corresponding to the strike, the spreading ridges of the Rieser-Larsen Ridge, is expected to be formed (Figure 2.2A). (Leinweber & Jokat, 2012).

The offshore area is deeply submerged passive margin and oceanic crust formed during Late Mesozoic to Cenozoic time. The Coats Land margin is characterized by a straight narrow shelf and a slope which expand to SW within the Central Weddell sea province (Kuvaas & Kristoffsen 1991). The WDML margin stands out compared to the adjacent one because of the step- like pattern of the continental- slope. The slope comprising a gently dipping mid-slope bench 80 km wide and it is bounded on the oceanic side by the steep cliff known as "Explora Escarpment" (Miller et

al.,1991). In the central part of the Lazarev Sea, where it has a sublatitudinal strike, the similar structure is located (Hinz et al., 2004). “The Explora Wedge (Hinz and Krause, 1982; Hinz et al., 2004) extends over a distance of 1.700 km along the continental margin of Dronning Maud Land Margin from 20°E to 30°W. Its landward extent is unknown and covered by floating ice shelves along the continental margin” (Kristoffersen et al, 2014) (Fig. 2.3).
The emplacement of plume seems to have led to rifting and initial plate separation. The rifting was accompanied by prolific volcanic eruptions whose products were deposited around continent- ocean boundary to form dipping reflector sequence. (Leitchenkov et al. 1996).

The impact of the Karoo asthenospheric plume at the early seabed spreading stage led to the formation of morphologically pronounced volcanic structures - the Maud Rise in the northwestern Lazarev Sea and the northern extension of the Astrid Ridge at the border with the Rieser-Larsen Sea (Figure 2.3).

According to Jokat, 2003, the origin of the first oceanic crust between Africa (Mozambique Ridge) and Antarctica (Riiser – Larsen Sea) was at around 155 Ma. The velocity of the rift propagation in the Weddel Sea was of 63 km/Myr between chrons M19N and M17N and it was happening from west to east; the separation of Africa and South America from Antarctica occurred at chron M14N with the beginning of stretching in the area of the South Atlantic at 155 Ma (Jokat, 2003)

The Astrid Fracture Zone is associated with excessive melting of the upper mantle material at the intersection of the spreading ridge with the transform fault at the early stage of the opening of the Indian Ocean. The Astrid Ridge was considered by Hinz and Krause (1982) to be of continental origin, although strongly modified by voluminous volcanism.

Leitchenkov et al. (2008) postulate a formation of the southern Astrid Ridge during the rift phase and of the northern Astrid Ridge during the early spreading phase between Antarctica and Africa 160 Ma. König and Jokat (2010) as well as Gohl et al. (2011) support this hypothesis. Bergh (1987) considered Astrid Ridge to be a volcanic edifice, and suggested that it is conjugate to the Mozambique Ridge off East Africa; the Mozambique Ridge is characterized by four main features which are associated with different stages of volcanic activity during the Lower Cretaceous.

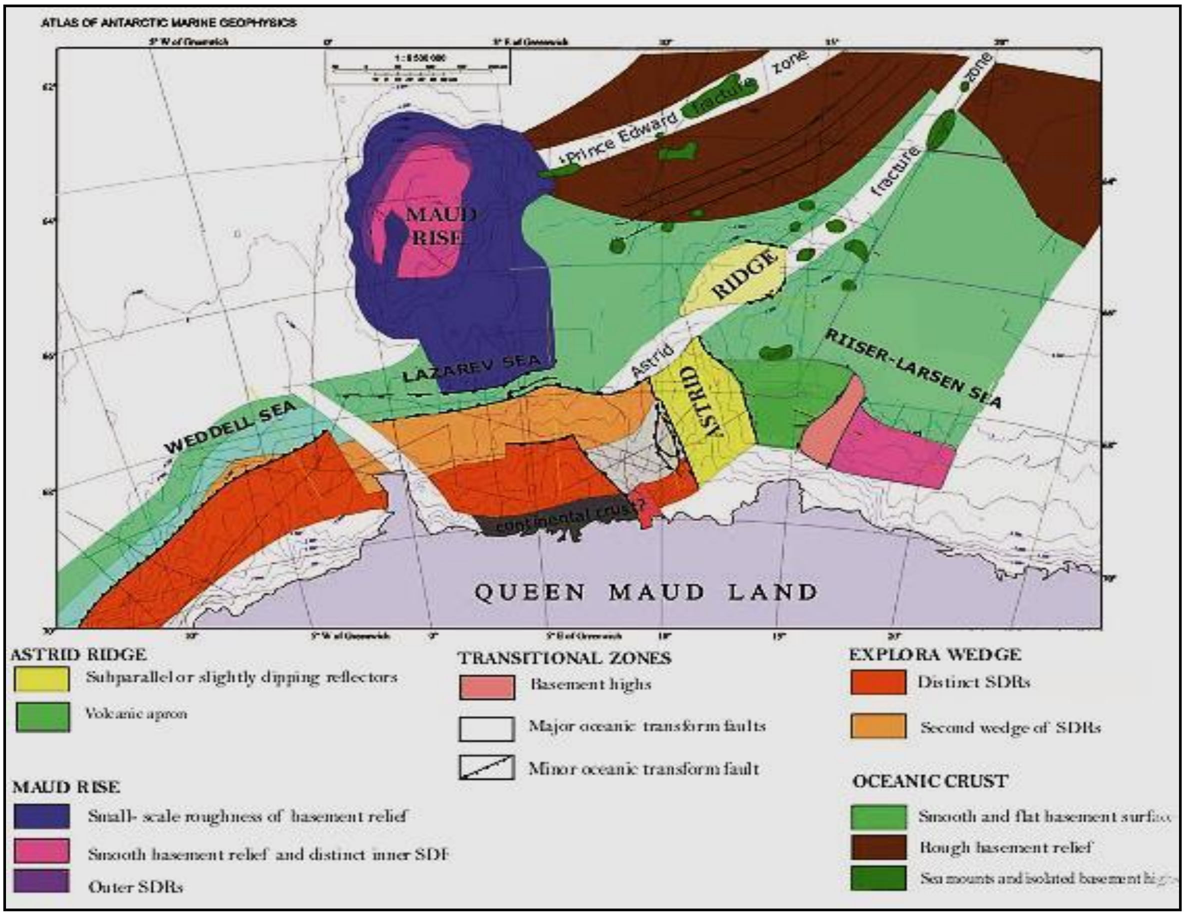

Figure 2.3 Main structural elements of Riser- Larsen, Lazarev and Eastern Part of the Weddell Seas *(simplified after Hinz et al, 2004)*

There are lots of discussions on the Mozambique Ridge origin; one of the hypothesis suggest that it belongs to the Large Igneous Province.

Fischer et al, 2017 correlate widespread post-sedimentary magmatic activity with a southward propagation of the East African Rift System. Based on their volumetric analysis of the southern Mozambique Ridge Fischer et al, 2017 infer a rapid sequential emplacement between ~131 and ~125 Ma, which is similar to the short formation periods of other Large Igneous Provinces like the Agulhas Plateau.

The Maud Rise may have a common evolution with the Northeast Georgia Rise and the Agulhas Plateau. Kristoffersen and LaBrecque (1991) infer that the Maud Rise as well as the Northeast Georgia Rise formed at a spreading centre. Drilling at the Maud Rise defined the basement to be of Campanian or pre- Campanian age, based on the oldest sediments dredged. This age is much younger than the assumed age of the oceanic crust upon which they are located; volcanic cones and sub-basement reflectors are present (Hinz et al, 2004)

3 Data and methodology

This chapter highlights the methodology used in order to assess the volcanic margins architecture and tectonic evolution of East Antarctica. The chapter is divided into two sections each focused on a set of data: 1) provided by Institute for Geology and Mineral Resources of the World Ocean (VNIIOkeangeologia, St.-Petersburg, Russia); 2) gathered and synthesized from the literature.

3.1 Seismic survey

The main seismic data set used as the basis for this study was acquired in 2010-2012 during 56th and 58th Russian Antarctic Expedition (RAE) onboard of RV "Akademik A. Karpinsky". This data set includes 6490 km of 2D multi-channel seismic data which covers the area of the eastern Weddell Sea and the Lazarev Sea. Seismic data were obtained using a 352-channel digital streamer and two lines of airguns of 1420-2340 cub. in. (23-38 l) of total volume.

The additional MCS reflection data were used in this study to allow reconstruction of conjugated volcanic margins of 1) Mozambique Ridge and Lazarev Sea; 2) Faulkland Plateau and Weddell Sea.

1) For the Mozambique Ridge seismic investigations were carried out by Alfred Wegener Institute for Polar and Marine Research in 2014. Totally, 4200 km of lines crossing the Ridge were acquired on board "RV Sonne" (during cruise SO 232) using 3000 m long 240 channel streamer using a cluster of 4 GI-guns ("Generator" 0.72l and the "Injector" 1.68 l)

2) Lamont-Doherty Earth Observatory and National Science Foundation data: about 4000 km of MCS data were acquired on board of "RV Robert D. Conrad" duting expedition RC2106 in 1978. This cruise was a multichannel seismic reflection study of the Falkland Plateau, Falkland Trough and North Scotia Ridge. In addition, 55 sonobuoy reflection and refraction profiles were recorded along the survey route to provide information on velocity structure.

3.1.2 Methodology

Using available seismic data the models of the conjugated volcanic margins of the Lazarev Sea and Mozambique Ridge; and the eastern Weddell Sea and the Falkland Plateau were constrained.

The following key crustal (tectonic) provinces and seismic horizons were interpreted on all chosen 2D lines: oceanic crust, stretched continental crust; SDRs.

The map which shows structural volcanic features of the East Antarctic passive margin was created, based on the analysis of the PMGRE seismic data which was obtained during 56th and 58th RAE expeditions.

3.2 Volcanic passive margins architecture

Volcanic margins are often associated with the large igneous provinces (LIPs) which are massive occurrences in a short period of time of mafic extrusive and intrusive rocks (White and McKenzie, 1989; Coffin and Eldholm, 1994). When volcanic margins are clearly associated with an abnormally thick adjacent oceanic crust and a hotspot track and tail, they are inferred to be related to lithospheric breakup over a mantle plume (Holbrook and Kelemen, 1993).

While there is a constant increase in a high-quality seismic data and now it is obvious that the breakup volcanism is common its level and volume can differ significantly (Coffin and Eldholm, 1994). The ability of identification of volcanic structures using the seismic data is important for understanding the nature and the consequences of the continental breakup magmatism (Planke et al, 2000).

Volcanic passive margins (Figure 3.1) are formed where continents breakup causing flood volcanism during prerift and/or synrift stages of the continental separation (Figure 3.2) (Holbrook and Kelemen, 1993). "There are two end-member extremes of passive rifted margins: (1) volcanic rifted margins (or else volcanic passive margins, VPM) and (2) magma-poor rifted margins (or else sedimentary passive margins, SPM). A breakup of the entire crust preceding breakup of the lithospheric mantle is a prerequisite for the exhumation of the mantle, one of the key findings at magma-poor margins, while at volcanic rifted margins the lithospheric mantle breaks before or at the same time with the crust to produce large volumes of syn-rift igneous rocks"(Franke, 2013).

VPM and SPM have distinct origins. They are respectively inherited from volcanic and sedimentary rifts. Sengor and Burke, 1978 first introduced the concepts of active and passive rifting from geological observations to account for the differences between, respectively, volcanic and non-volcanic rifts.

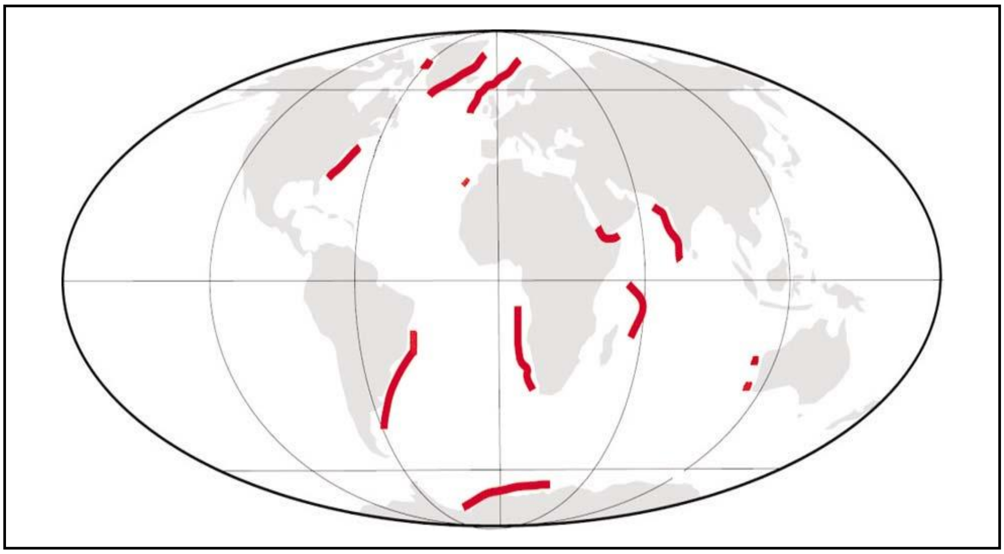

Figure 3.1 Worldwide distribution of volcanic passive margins (Callot et al, 2001)

Figure 3.2 summarizes some of the common concepts (or/and possibly, misconceptions) concerning both active and passive modes of extension (Geoffroy, 2005). According to the purely active model (Figure 3.2A), a hotter-than-normal mantle (for example, mantle plume) thermally thins the bottom of the lithosphere (Olson et al, 1988, Geoffroy, 2005). The two stages may be distinguished (Figure 3.2B): (1) flood-basalt stage, coeval with very small crustal extension and, (2), break-up stage associated with VPM edification. As a consequence of the breakup magmatism thermal subsidence occurs; its amplitude depends on the thikness of the new igneous crust and the presence of the thermal anomaly (Geoffroy, 2005).

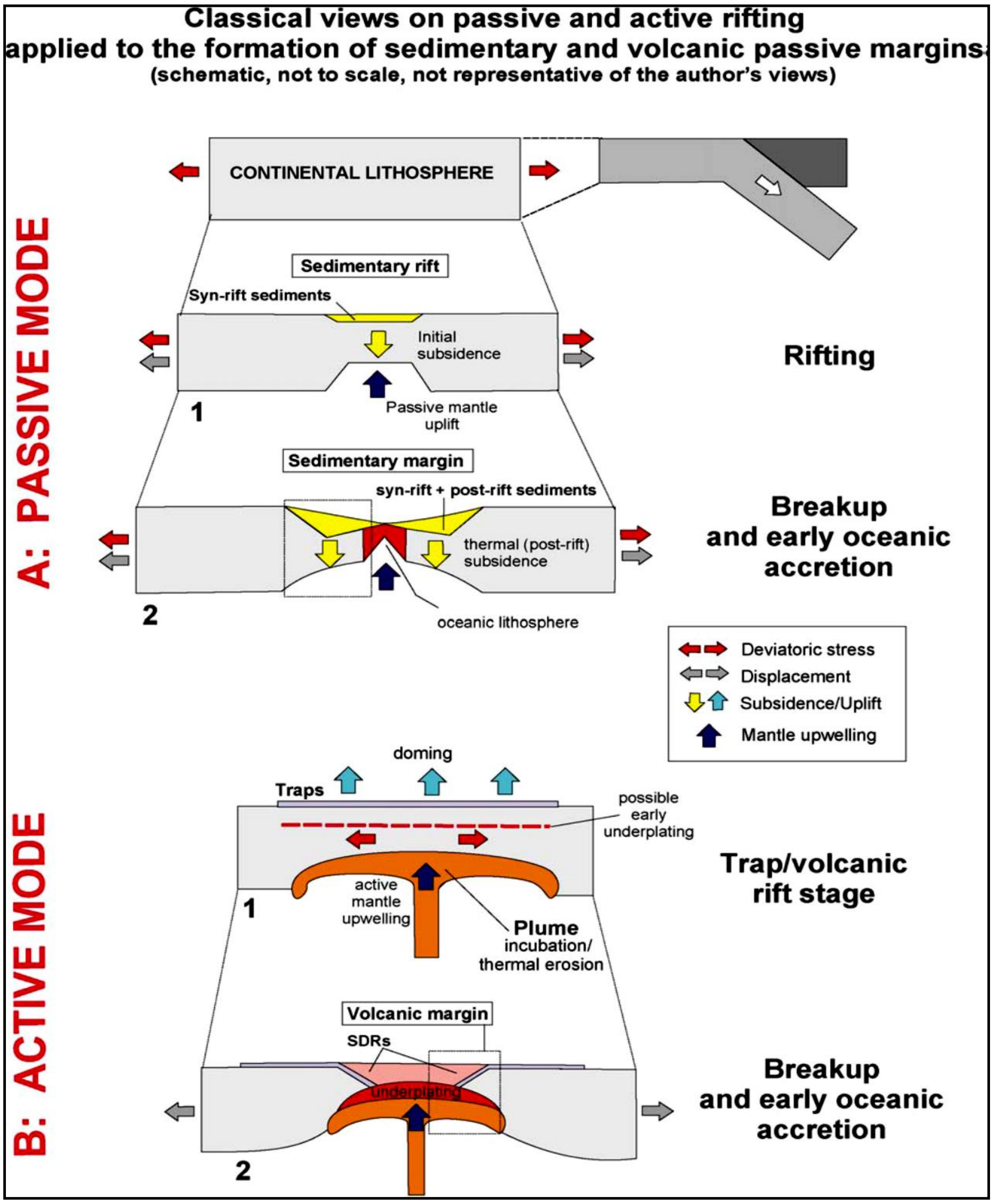

Figure 3.2. Passive (**A**) and active (**B**) mechanisms of lithosphere extension. (Geoffroy, 2005)

Planke et al, 2000 have identified four characteristic seismic facies units within the extrusive breakup sequence on the basis of published data and interpretation of numerous seismic reflection profiles in the northeast Atlantic, off Western Australia and in the south Atlantic (Figure 3.3).

These units are named:

(1)Outer SDR, (2) Outer High, (3) Inner SDR, and (4) Landward Flows (Table 2, Figure 6.3). Commonly, two additional facies units are identified: (5) Lava Delta and (6) Inner Flows.

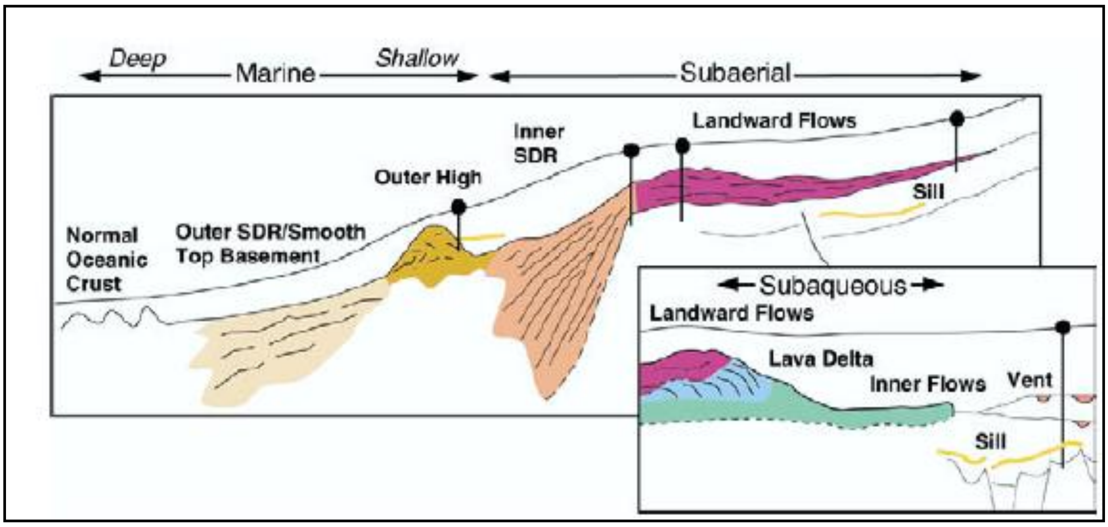

Figure 3.3 Schematic volcanic margin transect showing the volcanic extrusive seismic sequence (shaded) divided into tour seismic facies units. *Inset shows additional seismic facies units commonly identified in the northeast Atlantic. Proposed emplacement environment is shown by arrows. Wells (solid circle with vertical line) schematically located where drill holes penetrate corresponding seismic facies unit. SDR, seaward dipping reflectors (Planke et al, 1999)*

Landward Flows.

The Landward Flows unit is commonly identified on seismic profiles landward and below the Inner SDR. The Landward Flows unit frequently wedges out in a landward direction, for example, on the Namibian margin (Gladzcenko et al., 1998), the southeast Greenland margin and the Western Australia margin (Symonds et al., 1998). Along the European northeast Atlantic margin the unit usually terminates at a regional escarpment or merges with prograding reflections Lava Delta (Planke et al, 2005).

Lava Delta. The Lava Delta has an internal progradational reflection configuration. The upper unit boundary is determined by reflection terminations or a change in reflection geometry from fairly fiat-laying to disrupted, arcute events. The lower unit boundary is interpreted as a surface connecting the lower termination of the prograding reflections but is often more difficult to identify. *(Planke et al, 1999)*

Inner Flows. The Inner Flows is a sheet-like body of very disrupted or hummocky reflections located landward and below the Lava Delta . The top reflection is a high-amplitude, disrupted event. Internal reflection configuration is chaotic. The base is a weak negative-polarity reflection but is often difficult to identify (Planke et al, 2005)

Inner SDR. The Inner SDR top-basement reflection is typically a strong, continuous, smooth or wavy event, and toplap is commonly observed. The unit is wedge-shaped. Reflection terminations are common within the SDR. These are mostly nonsystematic but do sometimes define boundaries dividing the SDR into subunits (Planke and Eldholm, 1994). A base reflection is rarely identified, partly because of masking by strong sea floor multiples (Planke et al, 2005)

Outer High. The Outer High is a mounded feature characterized by a fairly strong top reflection, chaotic internal reflection configuration, and a location near the seaward termination of the Inner SDR (Planke et al, 2005)

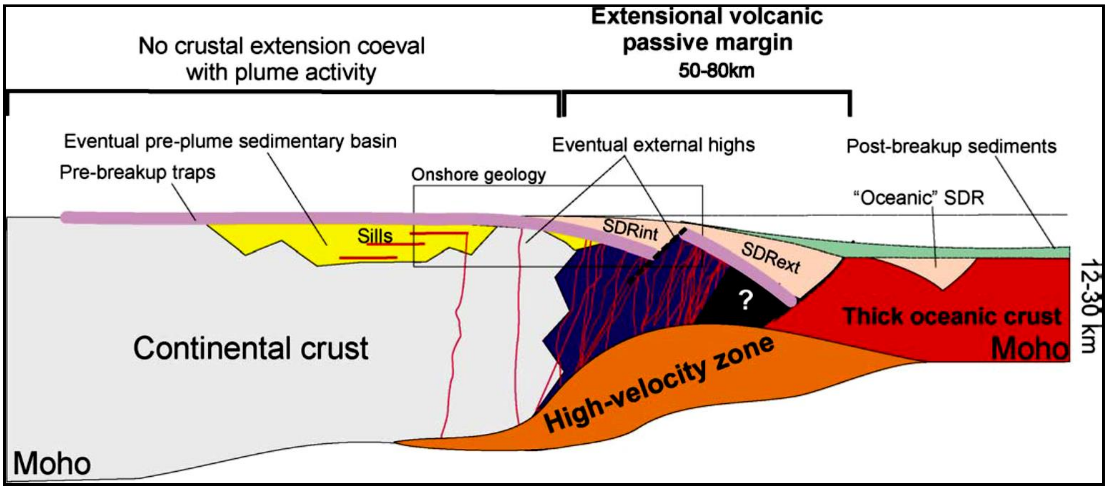

Figure 3. 4 Across-strike section of a volcanic passive margin. *The presence of internal sedimentary basins is not the rule. SDRint and SDRext: respectively, internal and external seaward-dipping lavas and volcanic projections (i.e. 'Seaward-Dipping Reflectors' in offshore studies) (Geoffroy, 2006).*

The rocks composing this element of extrusive complexes have not yet been tested by drilling, but it is assumed that they were mainly formed in the deep sea marine situation at the stage of early spreading under conditions of excess magmatism in the oceanic ridges, although the rear part of the outer wedge can also be located on the continental crust of the marginal graben (Leichenkov, 2012).

Outer SDR. Two sets of SDR units are observed on many volcanic margins, for example, on the Voring Margin (Skogseid and Eldholm, 1987) and the

Rockall/Hatton Bank Margin. Overall, the seismic characteristics of both SDR units are similar. However, the Outer SDR is smaller, with weaker, less prominent internal reflection . The Outer SDR are located seaward of the Outer High at greater water depths than the Inner SDR. It has a smooth top-basement reflection and a gradual transition to a normal, hummocky-type or smooth top oceanic basement reflection (Planke et al, 2005).

The general model of the volcanic margins is presented on the Figure 3.4. The lower part of the continental crust and adjacent part of the oceanic crust have higher seismic velocities from 7.2- 7.7 km/s (HVZ- high velocities zones) and densities from 3-3.15 15 g/sm3. It's formation is usually connected with the magmatic accretion and the result of this process is called "underplating" (Planke et al., 2000).

Seismic volcanostratigraphy is the study of the nature and geologic history of volcanic rocks and their emplacement environment from seismic data. A sequence is normally defined as a depositional unit of genetically related strata bounded by unconformities or their correlative conformities, whereas a seismic sequence is a depositional unit identified on seismic data. The method relies on seismic sequence analysis and seismic facies analysis as described by Vail and Mitchum (1977) (Figure 3.5).

In the seismic record, volcanic (extrusive) complexes have a specific wedge- shape structure, which is most often characterized by inclined (angle of incidence up to 15 °) and dipping towards the ocean by intermittent and continuous reflections of 10-15 km in length. The inclination of the reflections is caused by the gradual submergence of the earth's crust under the increasing load of the magmatic material. The term "Seaward dipping reflector Sequences" (SDR) has been established to denote the characteristic structure of volcanic complexes.

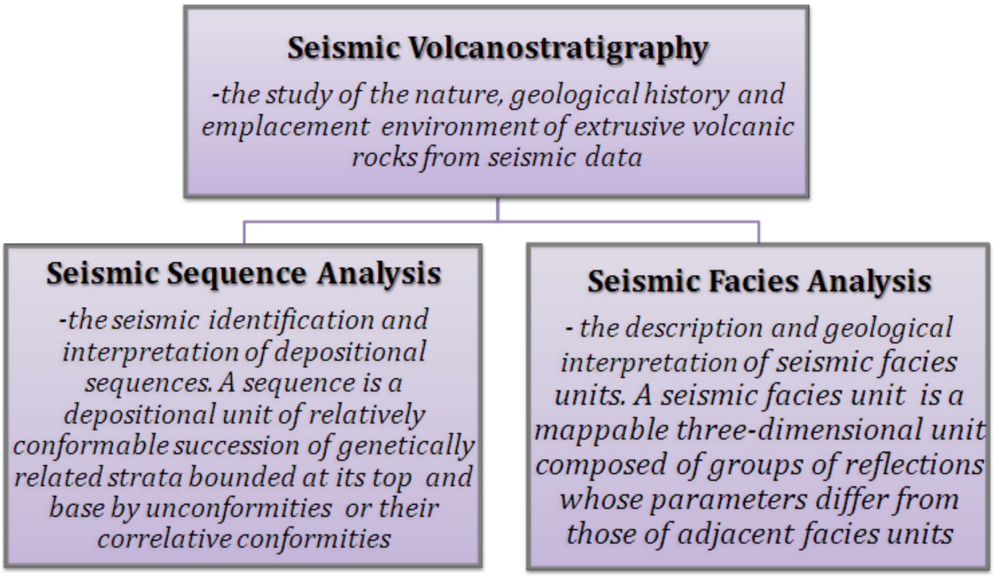

Figure 3.5 Definition of key terminology in volcanostratigraphy. *This study is mainly concerned with seismic facies analysis (modified from Planke & Alvestad, 1999)*

Seismic volcanostratigraphy relies mainly on seismic facies analysis, that is, the mapping and geological interpretation of seismic facies units. Volcanic deposits are commonly difficult to image by seismic reflection data as they are seismically very heterogeneous where intrabasement reflections primarily are interference phenomena or coherent noise such as converted waves and short multiples (for example, Planke and Eldholm, 1994). It is therefore difficult to interpret intrabasement reflections directly in terms of geology (Planke et al., 2000)

4 Results

4.1 Crustal structure of East Antarctic volcanic margin based on seismic data

4.1.1 Volcanic passive margins architecture

Following seismic stratigraphic concepts (e.g., Veil et al., 1977) ; Hinz, 1981 definition of SDRs, which are seismically imaged as strongly reflective Seaward Dipping Reflectors Sequences; and applying Planke, 1999 volcanostrtigraphy approach to the available seismic data set, the main volcanic facies (Outer SDR, Outer High, Inner SDR) were identified, mapped and analyzed.

Seismic data collected on the East Antarctic margin (in the eastern Weddell Sea and Lazarev Sea) show typical characteristic of volcanic margins. The presence of voluminous basaltic breakup complexes can here be inferred with interpretation of characteristic seismic reflection configurations such as SDRs. (Figures 4.1-4.4) . On the figure 4.2 both SDRs and its "underplating" as a results of magmatic accretion is observed.

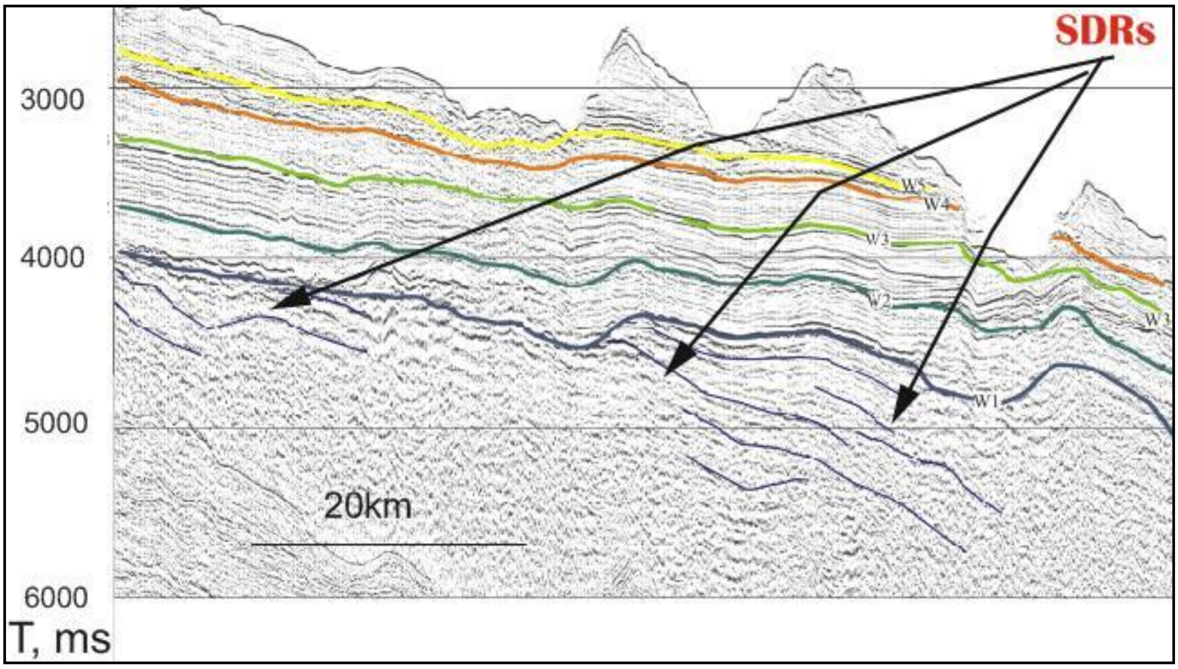

Figure 4.1 Part of the MCS line 5606. *It shows seismic sequence and seismic facies analysis with the following interpretation of horizons and three- dimensional structural features. For the location on map see figure 2.1.*

The velocities are high in these units with the P-wave variations from 4000- 5500 m/s (Figure 4.2-4.3).

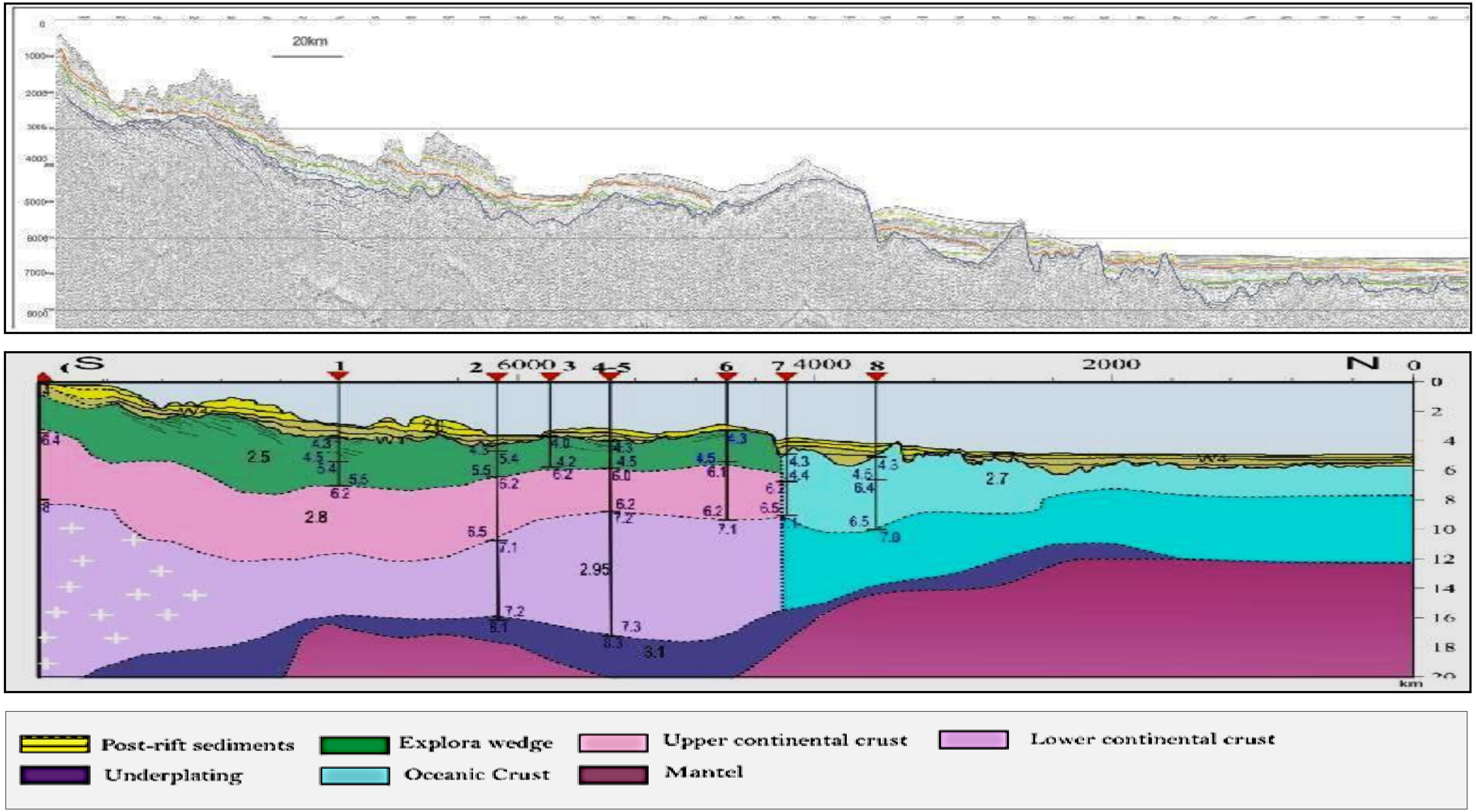

Figure 4.2 Seismic profile 5604 from Weddell Sea with the interpretations *(PMGRE, 56th RAE report). It also shows densities (in g/sm3) and velocities at the boarder of different horizons (in km/s)*

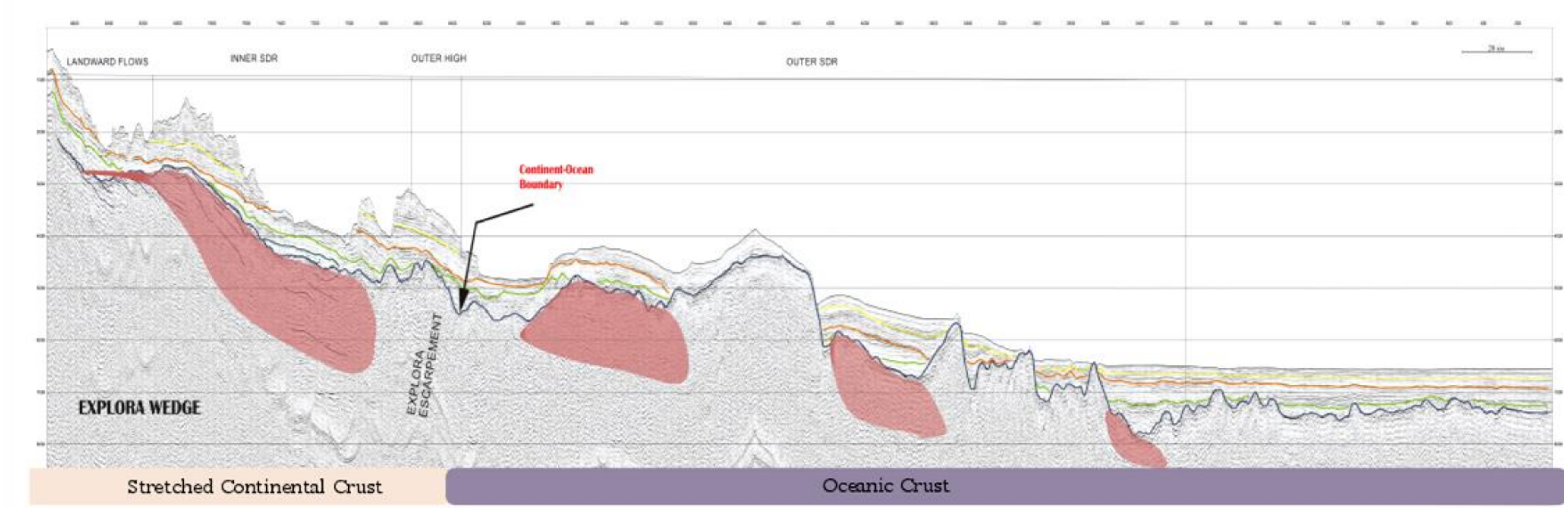

Figure 4.3 Seismic facies units interpreted along the profile 5604 from Weddell Sea. *It shows Inner and Outer SDRs separated by Outer High, Explora Wedge.*

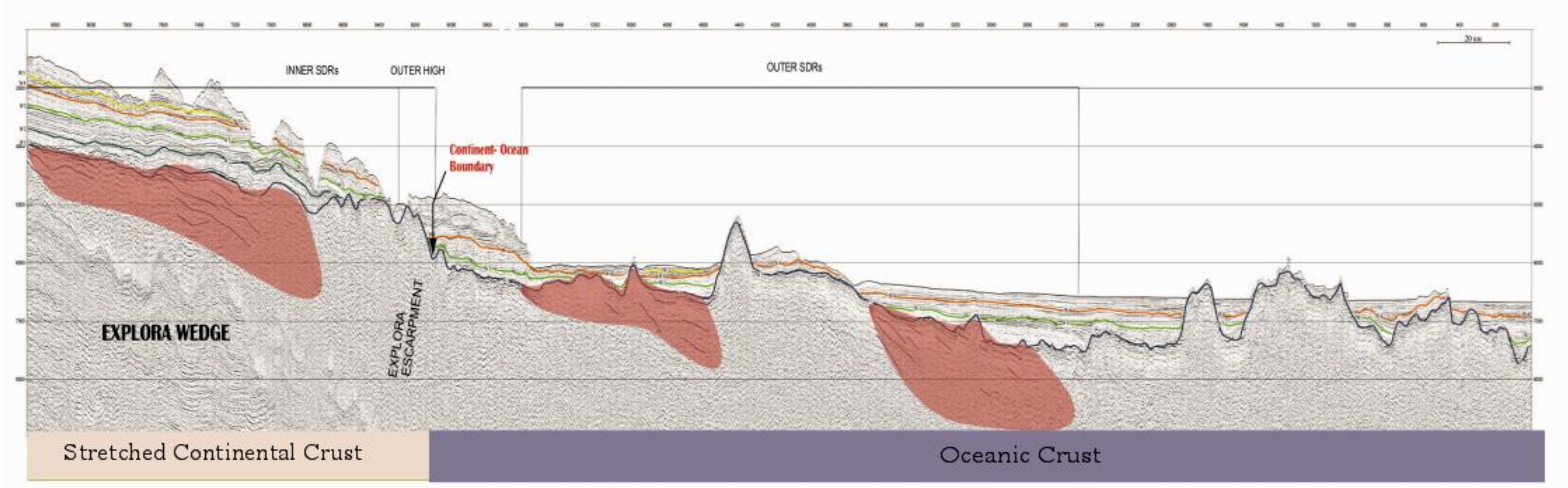

Fig 4.4 Seismic facies units interpreted along the *profile N5606 from Weddell Sea. It shows Inner and outer SDRs separated by Outer High, Explora Wedge*

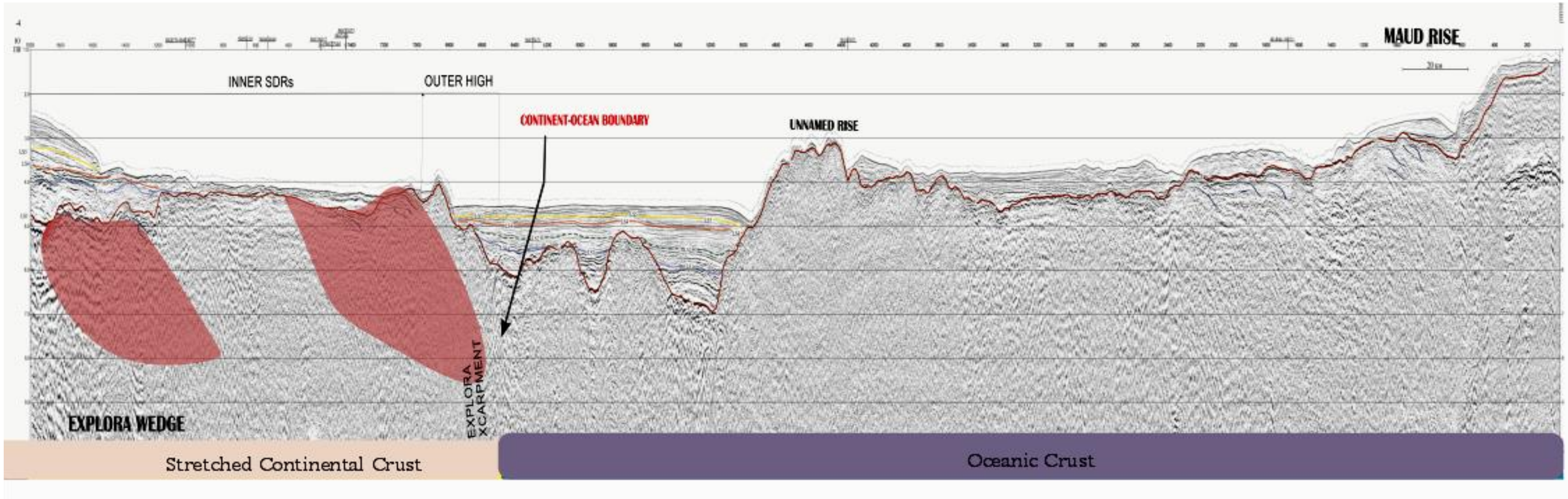

Fig 4.5 Seismic facies units interpreted along the *profile N5802 from Lazarev Sea. It shows Inner SDRs, Outer High, Explora Wedge, Maud Rise and Unnamed Rise*

The SDRs dip to the north, and individual reflectors are 5-25 km long (Figure 4.3-4.5).
The velocity of seismic waves in volcanic complexes varies from 3.5 to 5.6 km / s, but the lower horizons may have higher values (up to 6.0 km / s). The average density of the entire mass of volcanogenic rocks is 2.5-2.6 g / cm3. Despite the seismic stratification of volcanic complexes, their roof, which is a contrast and continuous boundary in the seismic record, is usually considered as an acoustic basement (Gladczenko et al, 1998; Hinz et al, 2004; Leichenkov et al, 2010).

On the profile 5604 (Figure 4.2) SDRs are mainly visible on the southern part, but there are flat-lying units which probably indicate eruptions below sea level. In the southern part of profile thickness of the sediments ranges from 600 to 2000m. Seismic velocities averages around 2000 m/s at this layer. In the northern part of the profile, velocities from 4000- 6500 m/s indicate upper oceanic crust. In the southern part of the profile 5604 velocities increase from 4300 to 5500 m/s. This part contains SDRs and represents Explora Wedge with the thickness of around 4 km. The higher seismic velocities of 8100- 8300 m/s are observed beneath the crust and connected with the magmatic accretion, representing "underplating". An extension of the Explora Wedge on the profile 5604 is about 230 km.

The Explora Wedge thickness in the study region can not be determined by the common depth point method. If we assume that the velocity of refracted waves of 5900-6200 m / s, obtained by the seismic refraction method for the profile 5604, corresponds to the surface of the crystalline base, then the thickness of the volcanic complex in the northern part of the continental slope is 2.5-3.0 km . Simulation of the gravity field shows that the thickness of volcanic sediments can increase up to 5-6 km toward the land. A similar estimation was obtained from magnetic anomalies on the profile 5606 (PMGRE 56th RAE report).

The crustal thickness is decreasing from 30-28 km on the shelf of QDML till 17-15 km near the Explora escarpement. Higher velocities and higher densities are observed at the lower part of the crust which indicates the presence of the intrusive material (the result of the "underplating" in the earth crust) (Figure 4.2)

4.1.1.2 Seismic volcanostratigraphy

Planke et al, 2000 interpretations of a high-quality seismic reflection data and well data on rifted margins suggest that it is necessary to refine the seismic interpretation procedure used to identify and map volcanic constructions.

The extent of the volcanic complex is interpreted on the base of its top reflectors, which are normally seen as a high- amplitude in the seismic record. Variations in reflections depend on lithological characteristics, thickness of lava and facies.

Following Planke et al, 2000 concept and seismic data from Weddell and Lazarev Seas, main volcanic facies have been identified :

1) Landward Flows 2) Inner SDRs 3) Outer SDRs 4) Outer High.

1) Landward Flows are generally seen behind Inner and they are located closer to the continental part of the margin; top reflections can be described as strong and smooth; internal reflections are disrupted and hummocky ; they were developed in subaerial environment (Figure 4.3);
2) Inner SDRs have high- amplitude and smooth reflections, the base can not be defined, this unit is wedge- shape and divided into subunits , the internal reflections are 5-20 km long with a general dip of < 15 °(Figure 4.3- 4.5), developed in subaerial environment;
3) Outer SDRs have similar characteristics to Inner SRDs, but are weaker and have smaller reflections. They are located seawards of the Outer High (Figure 4.4- 4.6) and developed in the marine environment;
4) Outer High is a mounded feature with a high amplitude reflections and are located close to seaward termination of Inner SDRs. The mounds are around 1.5 km high and 10 km wide (Figure 4.3- 4.5). They have been developed in subaerial environment and indicate the continent- ocean border.

Main features of the volcanic seismic facies are shown and compared with the peculiarities of the East Antarctic volcanic margin facies in Table 1.

Table 2. Dominant characteristics of main volcanic extrusive seismic facies units on rifted margins and comparison of its the emplacement environment and volcanic facies with the current study (modified from Planke et al, 2000)

Seismic Facies Unit	**Shape**	**Boundaries**	**Internal**	**Volcanic Facies**	***Volcanic Facies for current study***	**Emplacement Environment**	***Emplacement Environment for current study***
Outer SDR	Wedge	Top:high-amplitude, smooth. Base:seldom defined	Divergent-arcuate or planar. Disrupted nonsystematic truncations.	Flood Basalts mixed with pillow basalts, sediments and sills	Flood Basalts mixed with pillow basalts, sediments and sills	Deep- Marine	Deep- Marine
Outer High	Mound	Top:high-amplitude event. No Base	Chaotic	Hyaloclastic flows and volcaniclastics	***Flood Basalts***	Shallow-Marine	***Subaerial***
Inner SDR	Wedge	Top:high-amplitude, smooth. Base:seldom defined	Divergent-arcuate or planar. Disrupted nonsystematic truncations.	Flood Basalts	Flood Basalts	Subaerial	Subaerial
Landward Flows	Sheet	Top:high-amplitude, smooth. Base:low-amplitude, disrupted	Parallel to subparallel. amplitude, very disrupted	Flood Basalts	Flood Basalts	Subaerial	Subaerial
Lava Delta	Bank	Top:high-amplitude, or reflector termination. Base: reflector termination	Prograding clinoform. Disrupted	Massive and fragmented basalts. Volcaniclastics.	Massive and fragmented basalts. Volcaniclastics.	Coastal	Coastal
Inner Flows	Sheet	Top:high-amplitude, disrupted. Base: negative, but often obscured.	Chaotic or disrupted, subparallel	Massive and fragmented basalts. Volcaniclastics.	Massive and fragmented basalts. Volcaniclastics.	Subaquaeeous	Subaquaeeous

4.2 Tectonic Evolution of EA volcanic margin.

The tectonic map (Figure 4.5.1 shows main structural volcanic features of the eastern Weddell and the Lazarev sea. The Outer and Inner SDRs are observed on the map and the Outer High feature indicated the continent – ocean boundary. The presence of SDRs is decreasing towards the north, but the other volcanic constructions – Maud Rise, is observed on the north of the Explora Wedge. The Maud Rise is surrounded by rough basement relief. On the eastern part of the map another volcanic construction is located: the Astrid Ridge, which is adjacent to the Explora Wedge but also has its continuation in the northern direction, and the northern part is separated from the main part of the ridge with a prominent Astrid Fructure Zone.

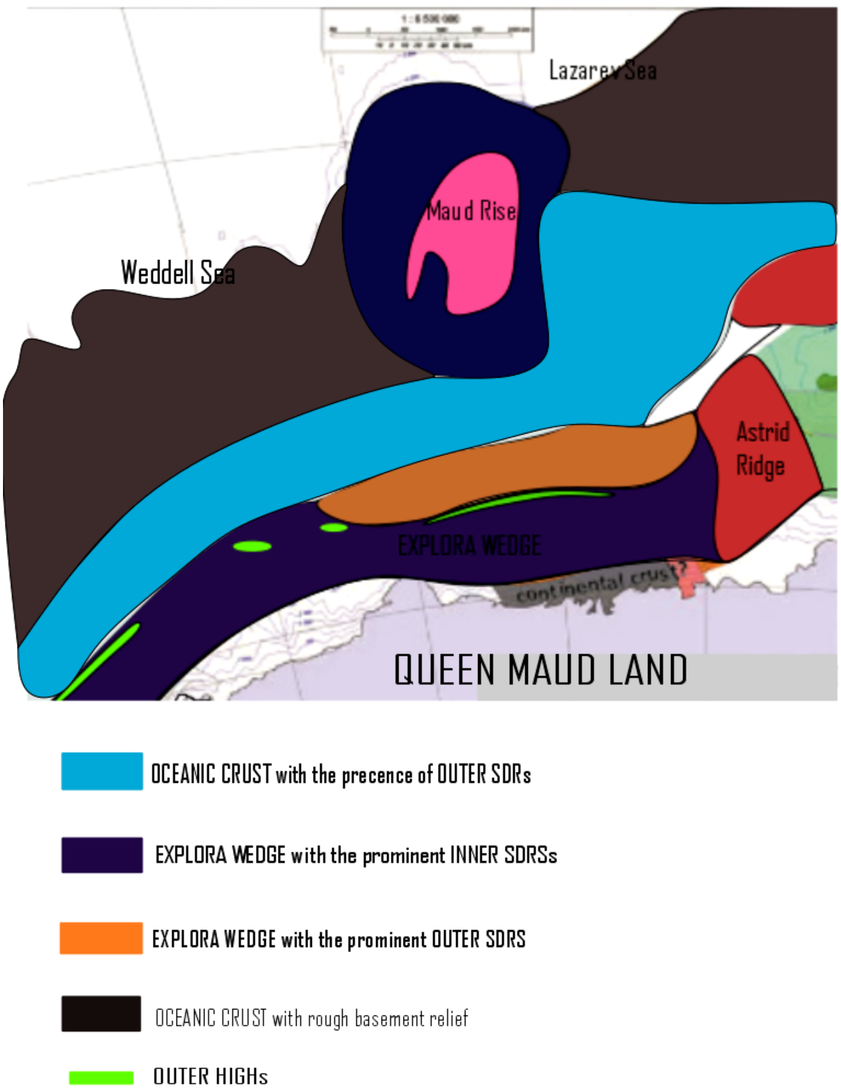

Figure 4.5.1 Tectonic Map. *It shows structural features of the eastern Weddell Sea and the Lazarev Sea.*

4.2.1 Correlation of conjugated rifted margins

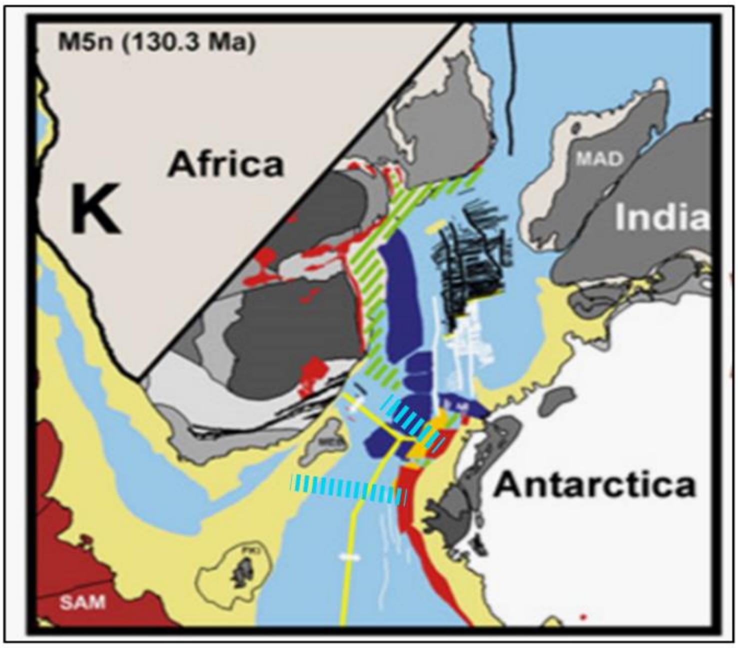

Figure 4.6 Kinematic model of Central Gondwana breakup for 130.3 MA. Conjugate margins are marked with light blue lines. *Regions marked with a green line pattern are considered as transitional crust. Spreading centres are indicated with yellow lines. Thin black and white lines show seafloor spreading anomalies. Thick black and white lines are fracture zones. Grey blocks are Precambrian and older crustal units. The beige areas are continental offshore crust. Light blue colours mark oceanic crust. Dark blue has been chosen to mark oceanic plateaus. The two SDRS-units of the Explora Wedge are shown in red and orange (modified after König and Jokat , 2006).*

The emplacement of the Karoo plume has long been recognized as a significant event in the geological history of southern Africa and Gondwana (e.g.Cox 1992) and potentially triggered the disruption of long-stable Gondwana as a single continent (Reeves et al 2016). In this part of the study author of the master thesis made an attempt to reconstruct conjugate margins which were formed as a result of Gondwana dispersion (Figure 4.6) which started in Early Jurassic (e.g. Reeves et al, 2016; Kristoffersen et al, 2017) or Early to Middle Jurassic (Eagles and Konig, 2008; Konig and Jokat, 2010; Leichenkov et al, 1996).

The crustal transects obtained in the current study outlines the crustal structure of the central Lazarev Sea and Falkland Plateau (Figure 4.10) and the eastern part of the Wedddell Sea and Central Mozambique Ridge (Figure 4.13) accordingly.

East Antarctica–Falkland Plateau

The Falkland Plateau is a rectilinear bathymetric feature in the South Atlantic Ocean which extends eastward from the South American continental shelf (Figure 4.7). A transform margin along its northern side accommodated a 1400 km offset between the continent-ocean boundary on the Argentine shelf and that to the east of Maurice Ewing Bank during the opening of this ocean, which commenced at about 130 Ma. Antarctica rifted away from the southern side of the Falk land Plateau at about 145 Ma (Jokat et al., 2003), and the Scotia Sea has developed on this side of the plateau in the last 30 Ma as a result of extension behind an eastward-migrating subduction zone (Kimbell and Richards, 2008).
Basement crops in the northern Escarpment and dredge sampling at the top of the Falkland Escarpment has collected a variety of large-sized (20 cm average diameter) igneous and metamorphic rocks having such compositions as gabbro, basalt, quartzite, slate, and gneiss (and the last being the most abundant). ln particular, the gabbro and basalt samples have only been found on the Escarpment's edge, near basement outcrops (Figure 4.8) (Lorenzo and Mutter, 1988).

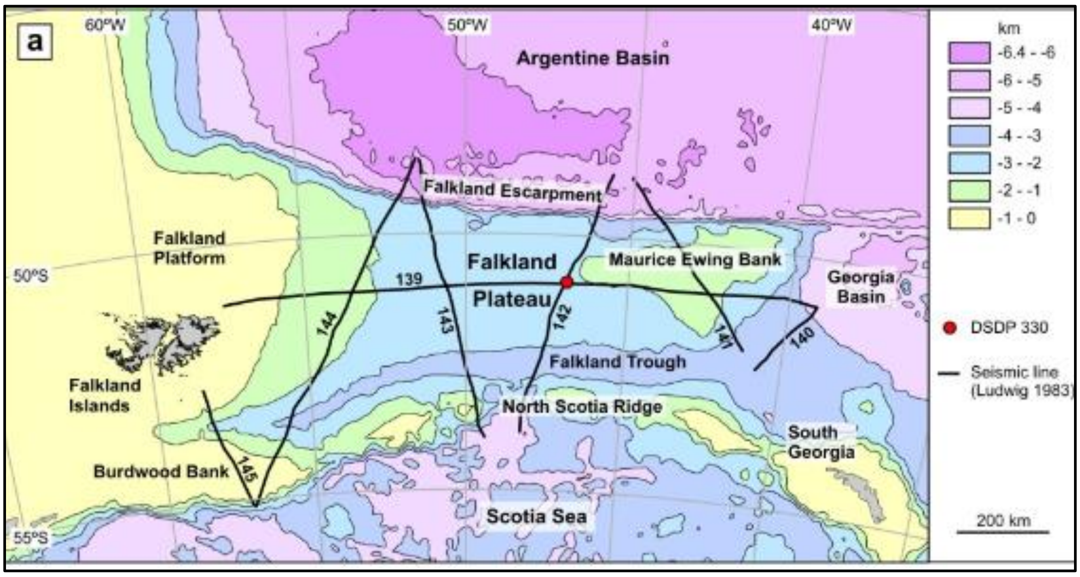

Figure 4.7 Bathymetric map of the Falkland Plateau region (Kimbell and Richards, 2008)

The Falkland Basin is confined to the north by a "marginal fracture ridge" (Figure 4.7)(Le Pichon & Hayes 1971) about 50 km wide and several kilometers above the contiguous basin floors. The ridge probably existed from very early in the development of the region because only the deepest and thus oldest Jurassic sediments are in any way affected by faulting. Moreover as seen on profile (Figure 4.8, 4.9) a very thick pile of (Middle?) Jurassic sediments onlap the ridge, showing no evidence of tectonic disturbance. The Falkland Escarpment is the northern exposed face of this ridge (Lorenzo and Mutter, 1988).

Dredged basalts and gabbros suggest some unknown amount of extrusive volcanic construction on the Escarpment and/or intense vertical block movement such as recorded at the equatorial fracture zones (Bonatti et ai. 1977).

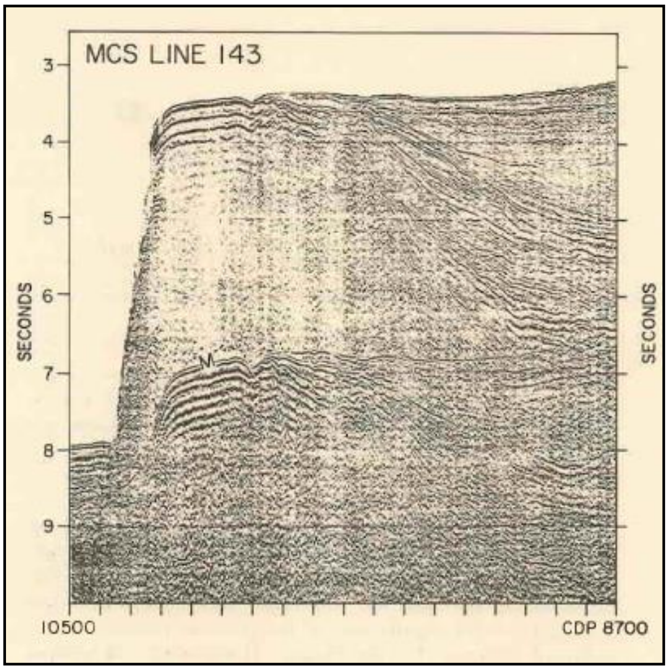

Figure 4.8- Multichannel seismic profile 143*. Its location is shown on the figure 4.7 (Lorenzo and Mutter, 1988)*

SDRs can be observed at several locations below the Faulkland Basin, but they are best developled on the southern slope of a local basement high.

They are seen as offlapping, and characterized by systematic decrease in dip towards the south (Figure 4.9) These characteristics have been interpreted as subaerial lava flows in areas of overthickened oceanic crust (Mutter et al, 1982), and could therefore be indicative of a volcanic basement for the central Falkland Basin (Lorenzo and Mutter, 1988).

It is not clear from the magnetic evidence whether fully oceanic basement underlies the Falkland Plateau Basin. Such basement could have been generated as a result of the rotation and translation of a Falkland Islands microplate in Early-Middle Jurassic times, or subsequently, as a result of the separation of the Falkland Plateau from Antarctica (Barker 1999).

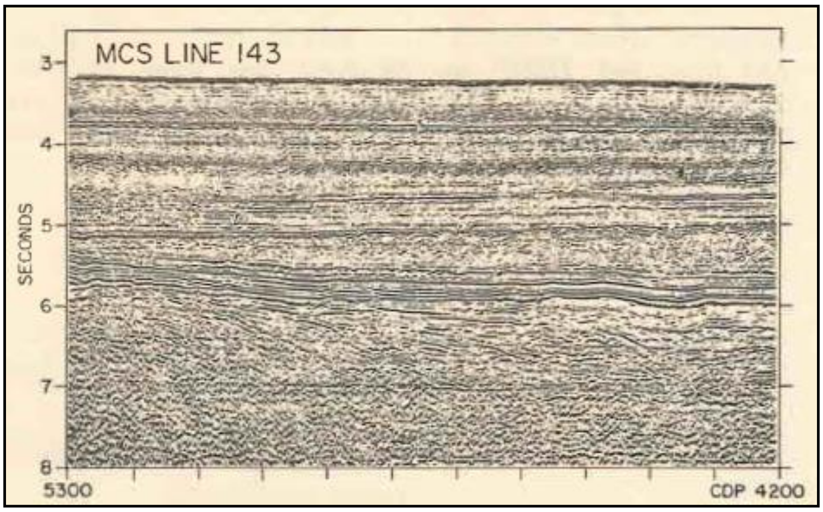

Figure 4.9 - Multichannel seismic profile 143. Its location is shown on the figure 5.2 *Dipping reflectors in the basement. Note the hummocky and oblique tangential rejlectors in the interval (Lorenzo and Mutter, 1988)*

Even if it exists beneath the southern part of the basin, oceanic crust is unlikely to extend to the northern Falkland Plateau, as continental basement is indicated there by tilted fault blocks and gneissic rocks in dredge hauls (Lorenzo & Mutter 1988). Gneissic continental basement rocks have also been found in dredge hauls along the top of the Falkland Escarpment, although such hauls also include basaltic rocks (Lorenzo & Mutter 1988). This hypothesis of the crust origin was used as a model in current study (Figure 4.9)

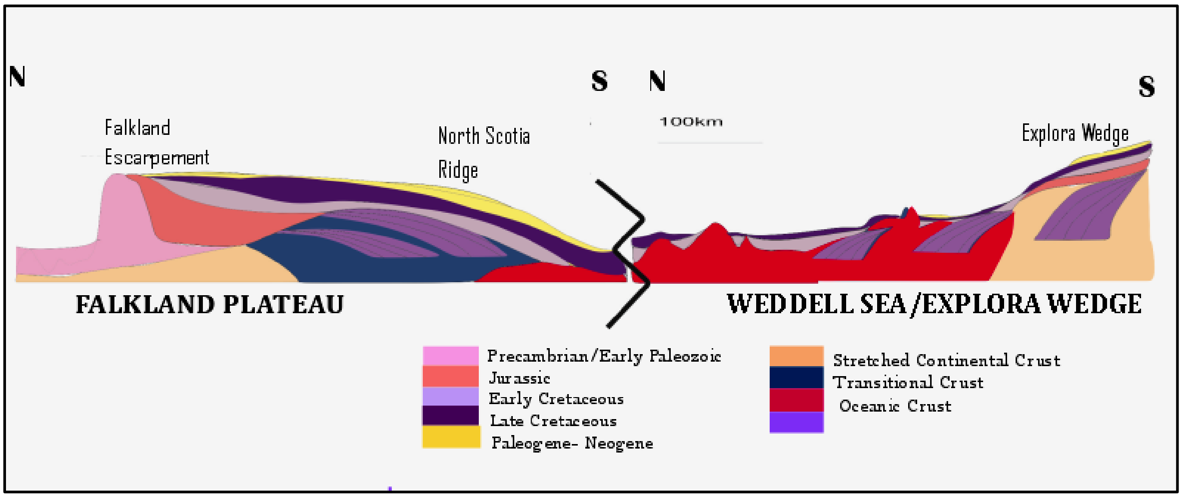

Figure 4.10 Conjugate transects of Falkland and Eastern Weddell Sea for 130.3 MA. *The location of conjugate margin is shown in Figure 4.6.*

Seismic profile MSC 143 was interpreted and used for the reconstruction; its location is indicated in Figure 4.7. Along the conjugate margin off East Antarctica (Figure 4.10), the representative crustal transect obtained from the interpreted seismic profile 5604 (figure 4.3), which was described in detail in section 4.1 of the current study. The location of the conjugate margins is shown in Figure 4.6.

East Antarctica- South Africa

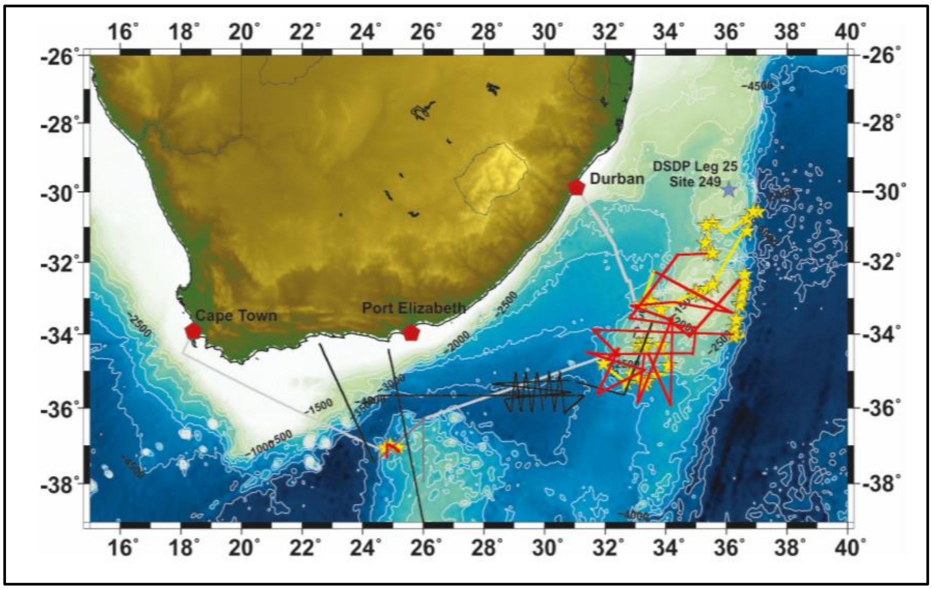

Figure 4.10 Overview map of the area of Mozambique Ridge. *Red lines show the seismic lines collecting during cruise SO232 (report AWI from the SO232 cruise, 2014)*

Authors have proposed several hypotheses about the nature and origin of the Mozambique Ridge (Figure 4.10), ranging from a continental provenance

(Hartnady et al. 1992), to an oceanic origin (Konig & Jokat 2010), to being partitioned into continental and oceanic parts (Ben-Avraham et al. 1995).

Based on the analysis of magnetic anomalies Konig & Jokat (2010) proposed a formation of the Mozambique Ridge between 140 and 120 Ma. Fischer et al, 2017 updated their ages of magnetic and suggested that central Mozambique Ridge was formed between 140 and 135.32 Ma and continued to grow until 125.93 Ma. Several scientists consider Mozambique Ridge, Astrid Ridge, Madagascar Ridge, and Gunnerus Ridge as continental fragments in their plate tectonic reconstructions of Gondwana, which results in overlap of those structures with larger units (Hartnady et al., 1992, Jokat, 2006). Micro plates for Mozambique Ridge and the Falkland Plateau were discussed as a solution (Lawver et al., 1999).

Other authors vehemently contradict the existence of small independently moving plates. Eagles and König (2008) eliminate this possibility and suggest, that Mozambique Ridge and Astrid Ridge have been formed already during the Karoo volcanism 183-177 Ma. Leitchenkov et al. (2008) postulate a formation of the southern Astrid Ridge during the rift phase and of the northern Astrid Ridge during the early spreading phase between Antarctica and Africa 160 Ma. König and Jokat (2010) as well as Gohl et al. (2011) support this hypothesis.

The volcanic characteristics of the eastern Lazarev Sea segment is very likely to be related to the same magmatic events leading to the Early Cretaceous crustal accretion of a Large Igneous Province (LIP) consisting of the separated oceanic plateaus Maud Rise, Agulhas Plateau, and Northeast Georgia Rise (Gohl and Uenzelmann-Neben, 2001) and to which also parts of the Mozambique Ridge may have belonged (Gohl, 2008).

The hypothesis that Mozambique Ridge has the same origin as the Lazarev Sea is investigated in this study and the reconstruction for conjugate margins is proposed (Figure 4.13). MCS profile AWI-20140217 (Figure 4.10-4.11) is studied here in more details to show the arguments supporting this theory.

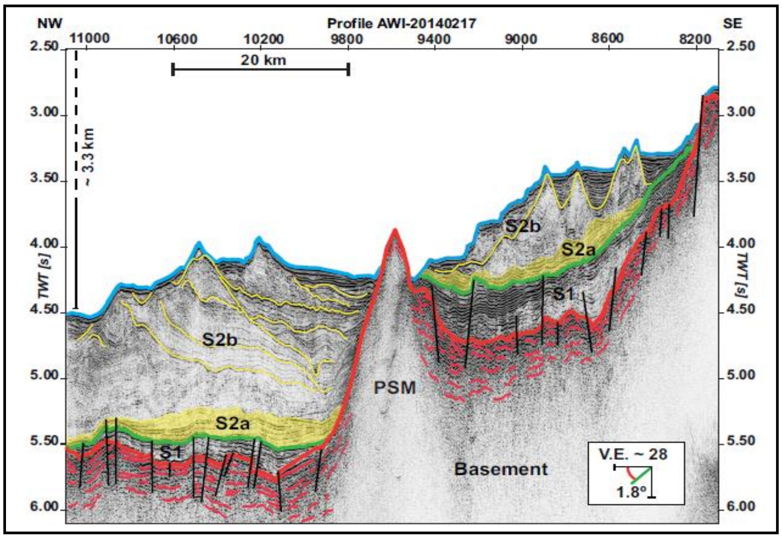

Figure 4.11 Mozambique Ridge (conjugate part of the Lazarev Sea) MCS profile AWI-20140217(Fischer et al, 2017)

The lowermost unit shows high amplitude, low frequency reflections (e.g. Figure 4.11 CDPs 10200–10600). Intrabasement reflections are located at the depth of about 500 ms (about 1-1.2 km) below basement surface. (e.g. up to 500 ms TWT in Figure 4.11 CDPs 9000-9400). The intrabasement reflections are strongest and at the top they are continuous and become significantly weaker at the lower depth as a result of the scattering and attenuation of the seismic signal. Individual reflections can typically be traced for 5–15 km. The intrabasement reflections overlaps in places and they dip away from local highs (e.g. Figure 4.12 CDPs 4000–4200). The top of the unit, which is marked red in MCS profiles (Figure 4.11, 4.12) has high impedance contrast with a sudden rise of the velocity to its overlying unit. This unit was interpreted as magmatic basement by Fischer et al, 2017. The basement at the central Mozambique Ridge characterized by an increase in dip to the NW and NE (Figure 4.12). Faults associated with the depressions show offsets of up to 1500 ms TWT (Figure 4.12 CDP 4800). The intrabasement reflections at the central Mozambique Ridge can be identified up to 800 ms TWT deep, and individual reflections are typically traced for 5–15 km.

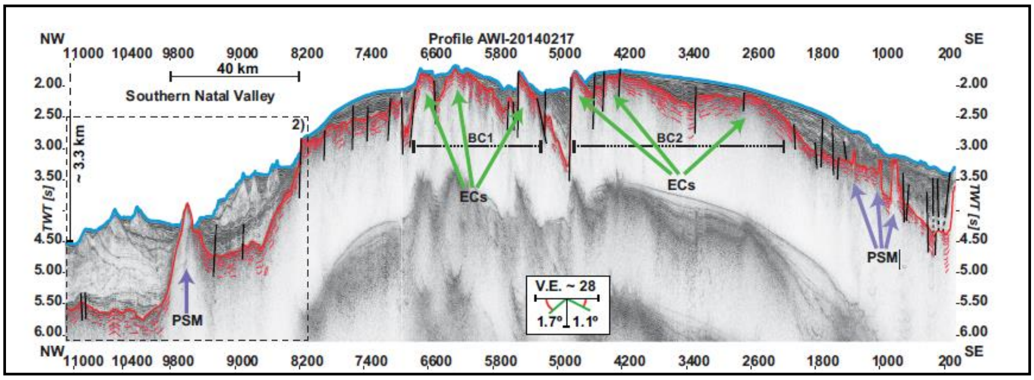

Figure 4.12 Mozambique Ridge (conjugate part of the Lazarev Sea) MCS profile AWI-20140217 crossing the central Mozambique Ridge in an NW–SE direction. *Thick blue line = seafloor, thick red line = top of basement, thin red lines = intrabasement reflections, black lines = faults, green arrows = extrusion centres (ECs), purple arrows = post-sedimentary magmatism (PSM). BC = Basement complex (Fischer et al, 2017)*

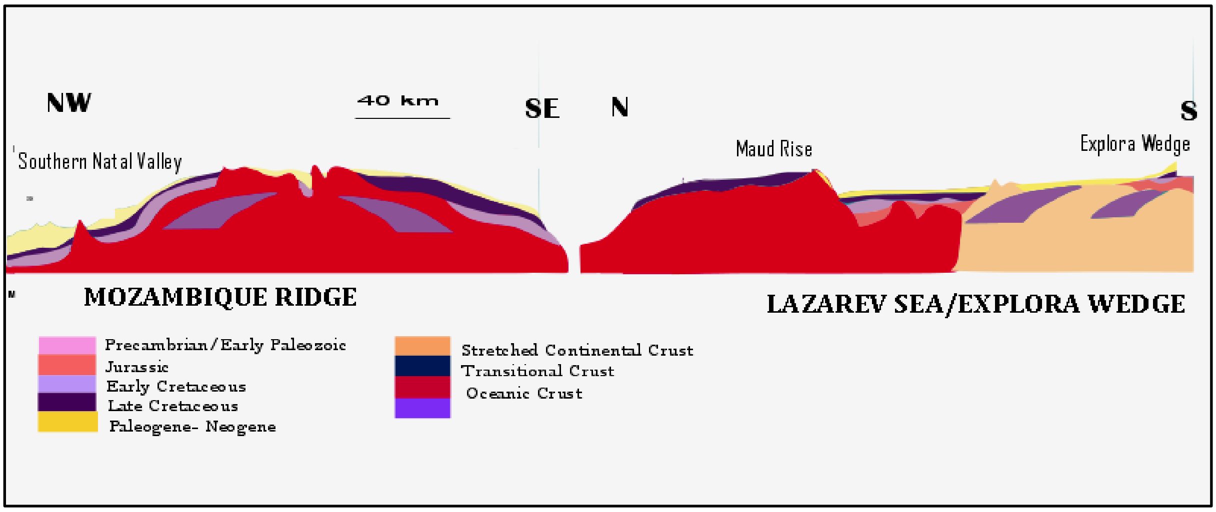

Figure 4.13 Conjugate transects of Central Mozambique Ridge and Lazarev Sea reconstruction for 130.3 Ma. *The location of conjugate margin is shown in Figure 4.6*

Along the conjugate margin off East Antarctica (Figure 4.13), the representative crustal transect obtained from the interpreted seismic profile 5802 (figure 4.5), which was described in detail in section 4.1.1.2 of the current study.

5 Discussion

The Mesozoic history of the South Ocean opening between Antarctica, Africa and South America is still poorly studied. Since the beginning of the Paleozoic, Antarctica was part of the supercontinent of Gondwana until its disintegration at about 180 million years ago. The early stages of rifting and disintegration of Gondwana were accompanied by abundant volcanism about 200 million years ago in the Karoo province (Leichenkov et al., 1996; Jokat et al., 2010). The abundant magmatism was caused by the rising of the mantle plume which had penetrated the lithosphere of central Gondwana (southeastern Africa-Eastern Antarctica), as a consequence a thermal anomaly of around 2000 km was created in the upper mantel and earth's crust was subject to stretching (White and McKenzie, 1989).In the Antarctic, the western part of the Queen Maud Land, located in the central zone of the thermal anomaly, was under the greatest influence of the plume. (Leitchenkov et al., 1996).The oldest anomaly in this area is of Late Jurassic and it is located in the southeastern part of the Rieser-Larsen (Jokat et al., 2003; Leitchenkov et al., 2008).

It can be suggested that rifting started from the west and continued clockwise. The sea bottom spreading in Lazarev Sea marked by changes in the direction and considering its complex geometry the transform faults are possibly present in the eastern part of the Weddell Sea (Leitchenkov et al., 2008; Leitchenkov et al., 2016) Three basins were formed in Jurassic: the location of the first was in the western Weddell Sea, the second was in the Rieser-Larsen Sea and the third was in the are of south-eastern Africa (Goodlad et al., 1982). Jokat et al. (2012) stated that separation of Antarctica has happened in two stages. The first phase occurred after the highest plume activity in the Karroo province (about 180 million years ago), Antarctica was rotated counter-clockwise relative to Africa during this stage. The second stage began about 159 million years ago, at about 152 million years ago the Antarctic undergone slight rotation clockwise while moving to the south. The new triple junction appeared 142 million years ago, as a consequence of the reorganization of the lithospheric plates in the Southern Ocean. The rate of spreading of the seabed possibly slowed down in the Weddell Sea between 126 million years and 118 million years, as a result of which to the north of 65 °S a system of closely spaced transform faults were formed (Leitchenkov et al., 2016).

5.1 East Antarctic volcanic margin formation and evolution

Early reconstructions of the southwestern margin of Gondwana overlapped the Antarctic Peninsula with Africa or the Falkland Plateau (Dietz &Sproll,1970).

The rotation of the Antarctic Peninsula in relation to Antarctica with the south of peninsula align to the Falkland Plateau was proposed by and de Wit (1977). The position of the continents for the 153.19 Ma (Reeves et al, 2008) is shown in Figure 5.1.

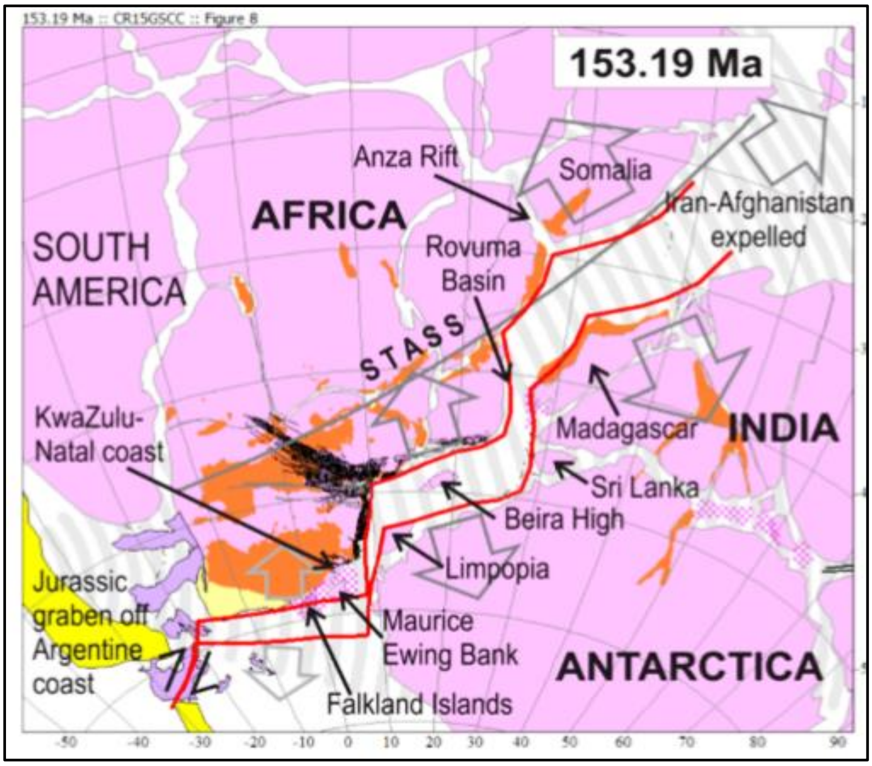

Figure 5.1 The Karoo rift and basin system (orange) in the context of the early (pre-153 Ma) opening between East and West Gondwana. *Red lines were conjugate in the 'fit' position (Reeves et al, 2008)*

In this study of the East Antarctica volcanic margins representative conjugate provinces are investigated:1) the East Antarctica–Falkland Plateau margin (Figure 4.10) and 2) the East Antarctica– South Africa margin (Figure 4.13).

1) The East Antarctica–Falkland plateau margin

According to Lorenzo and Mutter, 1988 the Falkland Plateau was undergone extension during the Middle Jurassic to Early Cretaceous.

The marginal fracture ridge was formed early in the Plateau history and according to the dredge-haul data it is composed of continental-type rocks as well as "oceanic-type" basalts. They speculate that thermal uplift may have been driven from heat input from an oceanic ridge passing along the Fracture Zone. A major

Jurassic/Cretaceous unconformity, marks the end of important tectonic activity on the Plateau (Figure 4.8, 4.10).

The conjugate transects of the Falkland Plateau shows signs of asymmetry, the SDRs of these margins have different configuration (only one set of SDRs is present in Falkland Plateau transect) and Outer High is not observed in case of Falkland Plateau (Figure 4.10). However, in both transects SDRs are seen as offlapping and its dip decrease towards the south in case of Falkland Plateau and towards the north in case of the Weddel Sea (Figure 4.10, 4.3).

Unlike in East Antarctic part thick Jurasic sediments is observed in Falkland Plateau (Figure 4.8, 4.10) which can indicate difference in after breakup tectonic history and low tectonic activity during Jurassic time in Falkland Basin. Since the oldest known sediments are Middle Jurassic in age, and most of the obvious faulting occurs in the lower parts of the first depositional sequence, rifting may have been taking place since at least the Middle Jurassic (Lorenzo & Mutter, 1988).

The evidence for volcanic activity in the basement of the central Falkland Plateau was noted by Lorenzo & Mutter, 1988; they refer this volcanic activity at least to the Middle Jurassic by making correlations with the age of the oldest sediments.

This age is in accordance with a formation of the Weddell Basin in the Jurassic (LaBrecque 1987).

Also, Richards et al, 2013, concluded that the Jurassic dykes can be considered a part of the regional Karoo-Ferrar magmatism linked to the initial break-up of Gondwana. They associated the Early Cretaceous magmatism of around 135 Ma with the stretching phases of the Falklands Plateau and rifting of the North Falklands Basin after the South Atlantic Ocean opening.

A crustal thickness of 11-12 km beneath the Falkland Basin is consistent with either a highly thinned continental section or a thicker than normal oceanic crust. Evidence for volcanism in the form of seamounts and dipping layers within the basement suggests that, if stretching of continental crust was involved, it was accompanied by significant melt generation (Lorenzo and Mutter, 1988) ; on the conjugated margin in the Weddell Sea Basin the thickness of the oceanic crust northwest of the Explora Escarpment is about 10 km, and it is most likely intruded by volcanic material at all crustal levels (Jokat et al 2005).

The extension of the Filchner Block in East Antarctica and Falkland Plateau Basin occurred between 184 and 175 Ma and the parallel between these events was noted by King, 2000. It was also suggested by Kimbell and Richards, 2008 that the lithosphere under the Falkland Plateau is stronger than one the east and west of it probably as a result of extension and underplating of continental crust and was formed under the influence of the Karoo-Ferrar plume and that the The Falkland Plateau possibly located adjacent to the Weddell Sea margin. The velocities of the structures below the Falkland Plateau are thought to be similar to the East Antartic margin charachteristics and indicate the presence of underplating at both margins.

2) The East Antarctica– South Africa margin

The inner dipping reflectors (SDRs) are considered coeval with the Karoo volcanism observed onshore Africa (Nguyen et al, 2016); outer formations are thought to be younger (150–138 Ma) and their formation is considered to happen after the initial breakup event (König and Jokat, 2010).

Taking into account COBs and fracture zones it was concluded that Antarctica began drifting away from Africa at approximately 171Ma in a SSE direction; margins were subject to extension from east to west (Nguyen et al, 2016). Their results suggest the extension of 60–120 km occurred in African part, while Antarctic crust was stretched by 105–180 km. The Mozambique Coastal Plain is covered by sediments that postdate the Karoo volcanism which took place during the period of 184–173 Ma (e.g. Cox, 1992) The underlying crust of the Mozambique Coastal Plain has been interpreted as thickened oceanic crust (Leinweber and Jokat, 2011; Eaglesand König, 2008) or thinned continental crust (König and Jokat, 2010; Cox, 1992).

The origin of the Mozambique Ridge is still under debate. Conflicting evidence have been presented to support for either a continental or oceanic origin (Leinweber and Jokat, 2011; König and Jokat, 2010). König and Jokat , 2010 proposed that it consists of an oceanic core surrounded by continental fragments and suggested that the abundant volcanism occured during the series of ridge jumps.

On the both conjugate margin the thicker than normal oceanic crust is observed (Figure 4.13). Apart from that, margins can be classified as asymmetrical. Only one set of SDRs is observed on Central Mozambique Ridge while in Lazarev Sea there are two sets of SDRS (inner and outer) and prominent Outer High feature which indicates COB (Leichenkov et al., 1996).

Seismic stratigraphy of the central Mozambique Ridge identifies two sedimentary units and the basaltic basement showing deep reaching intrabasement reflections known from other study areas and classified as lava flow sequences typical for LIPs.

Fischer et al 2017 proposed emplacement between 130.9–126.7 Ma in Central Mozambique Ridge (Figure 5.2) and the age correlate with the estimated age of the Maud rise. According to Leitchenkov *et al.*, 2008, the Maud Rise were formed during the stretching of the oceanic crust in transform fault under the influence of the Karoo Plume. Also, Leinweber and Jokat, 2012, the southwestern Mozambique Ridge was emplaced on a triple junction, which formed the Agulhas Plateau, the Robert-Giraud Plateau, the Rennell Plateau, the northern Astrid Ridge and the Maud Rise together as conjugate features later separating into their different parts.

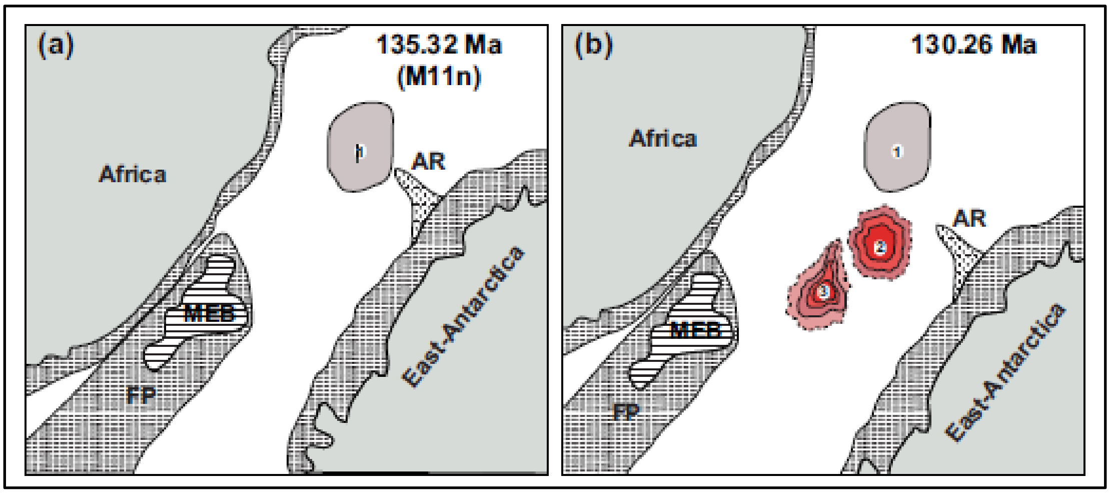

Figure 5.2. Schematic sketch of the proposed emplacement model for the southern Mozambique Ridge. *The framework conditions of the model are based on the plate tectonic reconstruction by Konig & Jokat (2010) (Fischer et al., 2017)*

5.2 Review of the East Antarctic Volcanic Margin crustal structure

The configuration of the rift before the onset of volcanic activity, its intensity and erosion determine the presence of each element of the volcanic complex. For this reason, volcanic complexes on different passive margins may differ slightly from the proposed model proposed by Planke, 2000 (Chapter 3.2). For example, as a result of the study of the passive margin near the coast of Namibia, a pronounced Outer High was not found in the structure of the volcanic complex (Elliott et al., 2009). The phenomenon was explained by the authors as a result of a rapid immersion of the earth's crust and a simultaneous weakening of volcanic activity. The East Antarctic volcanic margin differs from the model which was proposed by Planke et al, 2000.

The fundamental difference with the Planke et al, 2000 model that the Outer High volcanic seismic unit was developed in subaerial environment in the East Antarctica passive margin, and, moreover, it indicates the continent- ocean boundary. In the data used in this study there is no evidence of the landward dipping reflector which Gladczenko et al. (1998) suggested to be the termination of the SDR packages and the beginning of oceanic crust.

According to AWI aeromagnetic survey data, to the north of the Explora Escarpment, a distinct sequence of alternating magnetic anomalies has been observed; it is associated with the late Jurassic sea-bed spreading (Jokat et al., 2003; Leichenkov et al., 2016), the continent-ocean boundary is reliably determined by the foot of the Explora Escarpement (Figures 4.2-4.5)

All the above descriptions and interpretation of the data are systematized in Table 2.

The East Antarctica margin is inconsistent with the architecture of the North Atlantic volcanic rifted margins summarised by Planke et al. (2000) as an Outer High feature was developed in the subaerial environment and indicates the continent- ocean boundary in the case of East Antarctica volcanic margin (Figures 4.3- 4.5, Table 2), while this is common on another volcanic margins such as Western Australia margins (Planke et al, 2000), the North Atlantic margins (Hinz et al. 1999; Franke et al. 2007)and NW Australia (Symonds et al. 1998). Another exception is SW African and its conjugated Argentine/Uruguayan margin , where Outer High feature is less common (Elliot et al, 2009).

In the model of volcanic rifted margins proposed by Planke et al. (2000) based upon the architecture of the North Atlantic volcanic margins the outer highs form as the margin subsides with the fissure systems changing from sub-aerial eruption, responsible for the inner SDR to submarine eruption producing the Outer SDR's (Figure 4.3-4.5) The transition from sub-aerial to shallow marine promotes eruptive volcanism producing the hyaloclastite Mounds (Table 2) (Elliott et al, 2009).

This suggests that East Antarctic volcanic margin architecture is different from North Atlantic volcanic margins and as a consequence, the history of its development also differs. The nature of the Outer High and the escarpement in the Weddell Sea is still under debate. But, considering the seismic data from the PMGRE 56th and 58th RAE expeditions, it is possible to conclude, that this uplift is a volcanic chain. It was orginated by the outflow of lavas to the cracks and ruptures, which were formed by Earth's crust stretching. It has the same density as the Explora wedge, and it can be concluded that the main volcanic facies are flood basalts, unlike the Planke et al, 2000 . They suggested that the main volcanic facies of the Outer High are hyaloclastic flows and volcaniclastics. It can be concluded that Planke et al, 2000 model is not universal and it is not applicable in other regions.

Brune, 2016 suggested, that segmentation occurs during initial rifting and it can be characterized by segmenting almost parallel. For example, segmentation is observed in the southern South Atlantic (Koopmann et al., 2014) and in Greenland (Figure 5.3) (e.g., Tsikalas et al., 2005), although some segment boundaries (or "transfer zones") are still in question (Olesen et al., 2007).

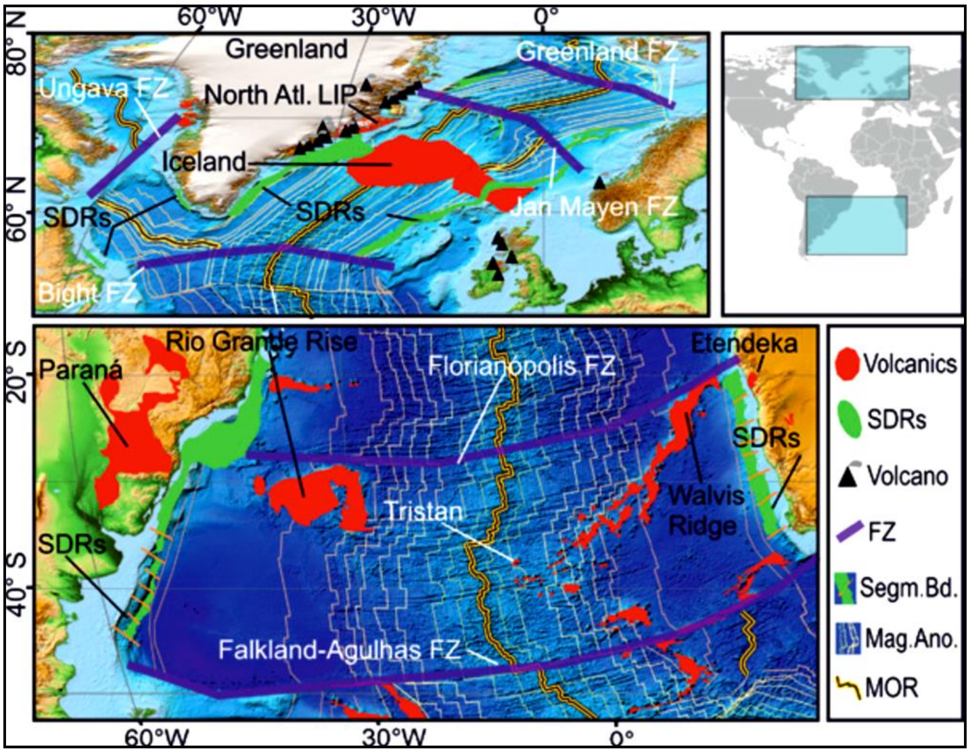

Figure 5.3 Map of the South and North Atlantic (Atl.).*It shows offshore and onshore large igneous provinces (LIPs), magnetic anomalies, and other structural elements. Margin segments are defined by structural variations across segment boundaries. Structures are from Bryan et al. (2010), Courtillot et al. (2003), Franke et al. (2007),*

and Koopmann et al. (2014a). SDR—seaward dipping reflector; FZ—fracture zone; MOR—mid-oceanic ridge; Mag. Ano.—magnetic anomaly; Segm.Bd.—segment boundary (Koopman et al., 2014b)

According to Koopman et al., 2014, the rift-parallel flow is a result of a lateral pressure gradient between continuously opening segments; increasing temperatures and decompression melting are caused by hot flow material near the segment boundaries; no increase in crustal thinning occurs near the transfer zones and peaks in pre-break-up melt are generated (Fig. 5.4). As a consequence, melt generation near the transfer zone is increasing by faster shallow mantle flow (Fig. 5.4C).

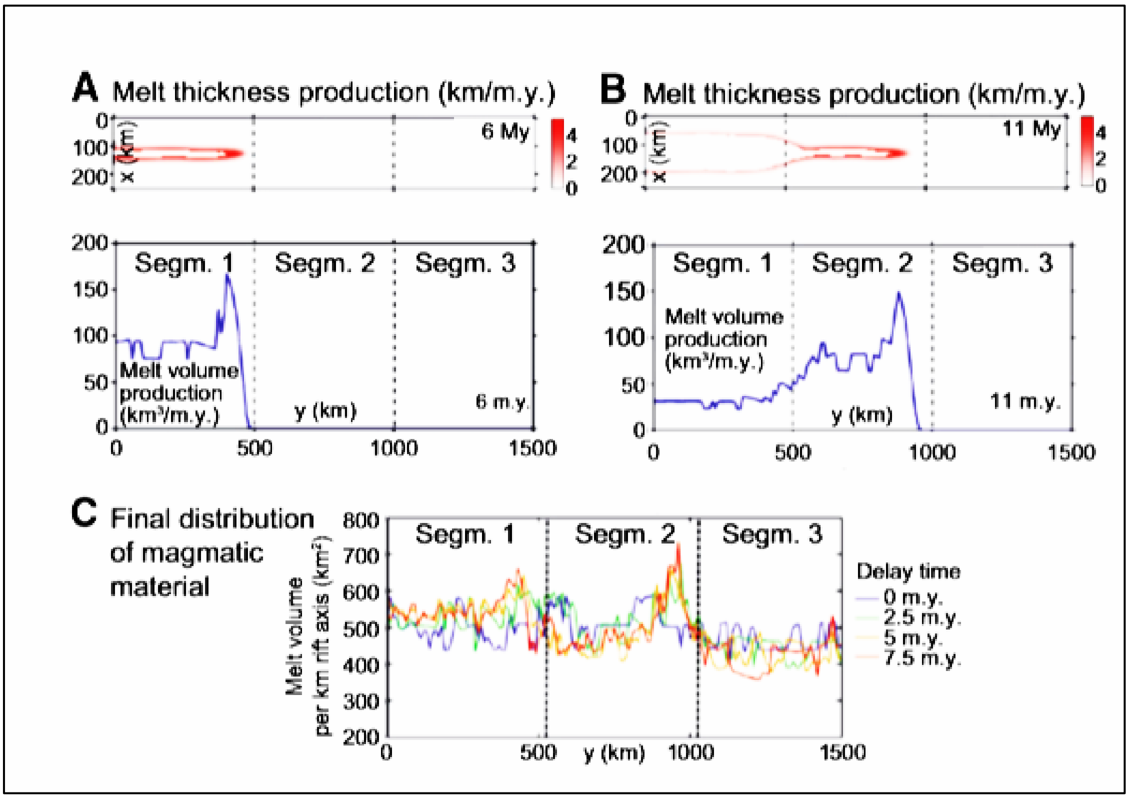

Figure 5.4. A, B: Upper panels: Production of igneous crustal thickness over time, at 6 m.y and 11 m.y. Lower panels: Igneous crust production integrated along the *x*-axis comparable to total melt emplacement at continental margins, at 6 m.y and 11 m.y. Melt production peaks after activation of segment 2 at 6 m.y. Viscous coupling forces peak production off imposed segment boundary at 500 km. Melt production peaks a second time at newly formed segment boundary at 11 m.y. C: Melt production indicates the importance of rift-delay duration (Koopmann et al., 2014b)

Rift-parallel flow of mantle can raise the along-strike volume of magma (Franke, 2013) creating SDRs in the distinct triangle shape form. As it was noted by Koopmann et al., 2014b, the initial position of rifting in the North and South Atlantic was situated away from hot-spot position (Iceland and Tristan, accordingly) and the rift migration was directed toward the hot-spot location with a persistent delay in break- up at the proposed position of hot- spots and the position of excessive magmatism.

As it was stated before, SDRs are also observed in the East Antarctic volcanic margin and they form the segmented margin (e.g. Planke et al., 1991) It is possible to draw a parallel between the development of the East Antarctic tectonic margin with its provinces and North and South Atlantic margins. While the margin of the WDML characterized by the highest amount of the basalts in comparison with the Coats Land (Leitchenkov *et al.*, 1996; Leitchenkov & Masolov, 1997) and the WDML is situated at the hotspot location (Karoo Plume), tectonic provinces of the East Antarctica are located distal from the hot-spot position as in the Atlantic Ocean LIPS described by Koopman et al, 2014. Gondwana separation probably was caused by continued rising of the upper mantle and astenosphere, which was occurring together with volcanism but it was already happening on the oceanic crust. As a result the Andenes plateau -Polarstern Bank (Weddell Sea) in the Late Jurassic times and the Maud Rises (the Lazarev Sea), as well as the Mozambique Ridge and the Agulhas Plateau (near southeast Africa) were formed in the early Cretaceous (PMGRE report, 56^{th} RAE).

According to Duncan, 1997, intrusive and effusive magmatism caused by Karoo plume started 200-170MA indicating the first stages of rifting in Gondwana; the Explora considered to be developed as a result of this events with the same age development (Hinz, 1981; Eldholm et al., 1994; White & McKenzie, 1989; Leitchenkov et al., 1996). However, Jokat et 2003, found the sequence of magnetic anomalies M19-M16 with the age of 150-145 million years at the region adjacent to Explora and they concluded that the age of Explora is much younger that the continental magmatism. Nonetheless, differences in the estimation of the age formation of Explora wedge (Middle Jurassic) and the East Weddell Sea crust based on magnetic anomalies by Jokat et al, 2003 (Late Jurassic) can be explained by the changes in strain localization which controlled by in depth magma distribution (Corti et al., 2004) and causing the shift in the axis of the spreading.

Similarly to North and South Atlantic excess magmatism at rifted margins (Koopmann in al, 2014), rifting in the East Antarctica probably occurred with the excess magmatism while opening has happened from the Risser-Larsen to the Weddell Sea .

Conclusions

The integration of the seismic data to the research of the volcanic margin crustal structure was used successfully and it is proven to be a reliable source of information for the characterization of the volcanic margins structure. The extent continent- ocean boundary in the eastern part of the Weddell Sea and in the Lazarev Sea was defined. The result of the work is presented in the form of the profiles with the classification of the East Antarctic volcanic margin units, the application of the classification was based on the existing models and the conjugate margins of the East Antarctica and Falkland Plateau and Mozambique ridge were reconstructed; the relatively new model of the rift segmentation and its linking to the excess magmatism was discussed and attempt to apply it to the East Antarctic volcanic margin was done. The following conclusions have been done:

- the existing volcanostratigraphy model of North Atlantic can not be applied to the East Antarctic volcanic margin in full and it suggests that East Antarctic volcanic margin architecture is different from North Atlantic volcanic margins and as a consequence, the history of its development also differs;
- East Antarctic volcanic margin and Falkland plateau were developed under the influence of Karoo volcanism but reconstracted margins show signs of asymmetry;
- East Antarctic volcanic margin and Mozambique show signs of asymmetry; both volcanic units were formed in the situation of Karoo volcanism, but East Antarctic margin undergone significantly higher stretching and was moving away in the SSE direction relatively to Africa what could possibly influence the geometry of the volcanic margin;
- The rift segmentation in East Antarctica could probably contribute to the direction of the sea opening from the Risser-Larsen Sea to the Weddell Sea by causing change in strain localization and the delay in breakup consequently.

References

1. Barker, P. F., 1999. Evidence for a volcanic rifted margin and oceanic crustal structure for the Falkland Plateau Basin*. Journal of the Geological Society, 156(5), 889-900.*

2. Ben-Avraham, Z., Tibor, G., Limonov, A. F., Leybov, M. B., Ivanov, M. K., Tokarev, M. Y., & Woodside, J. M. (1995). Structure and tectonics of the eastern Cyprean Arc. *Marine and Petroleum Geology, 12(3), 263IN1271-270IN2.*

3. Bergh, H. W., 1987. Underlying fracture zone nature of Astrid Ridge off Antarctica's Queen Maud Land. *Journal of Geophysical Research: Solid Earth, 92(B1), 475-484.*

4. Bonatti E., Sarnthein, M., Boersma, J.,1977.Neogene crustal emersion and subsidence at the Romanche Fracture Zone, Equatorial Atlantic Earth Planet*, Sci. Lett.; 35, 369-383.*

5. Brune, S., 2016. Rifts and rifted margins: A review of geodynamic processes and natural hazards*. Plate Boundaries and Natural Hazards, 219, 13.*

6. Coffin, M. F., and Eldholm, O., 1994. Large igneous provinces: crustal structure, dimensions, and external consequences. *Reviews of Geophysics, 32(1), 1-36.*

7. Callot, J. P., Geoffroy, L., Aubourg, C., Pozzi, J. P., and Mege, D. , 2001. Magma flow directions of shallow dykes from the East Greenland volcanic margin inferred from magnetic fabric studies*. Tectonophysics, 335(3), 313-329.*

8. Cox, K. G.,1992. Karoo igneous activity, and the early stages of the break-up of Gondwanaland. *Geological Society, London, Special Publications, 68(1), 137-148.*

9. De Wit, M. J., 1977. The evolution of the Scotia Arc as a key to the reconstruction of southwestern Gondwanaland*. Tectonophysics, 37(1-3), 53-81.*

10. Dietz, R. S. and Sproll, W. P. ,1970. Fit between Africa and Antarctica: a continental drift reconstruction. *Science, 167(3925), 1612-1614.*

11. Eagles, G., & König, M., 2008. A model of plate kinematics in Gondwana breakup. Geophysical Journal International, 173(2), 703-717.

12. Eldholm O. & Grue K., 1994. North-Atlantic volcanic margins: Dimensions and production rates: Journ. Geoph. Res., V. 99, 2955–2968.

13. Ferraccioli, F., Jones, P. C., Curtis, M. L., and Leat, P. T., 2005. Subglacial imprints of early Gondwana break-up as identified from high resolution aerogeophysical data over western Dronning Maud Land, East Antarctica. *Terra Nova, 17(6), 573-579.*

14. Franke, D., 2013, Rifting, lithosphere breakup and volcanism: Comparison of magma-poor and volcanic rifted margins. *Marine and Petroleum Geology, v. 43, 63–87.*

15. Elliott, G. M., Berndt, C., and Parson, L. M., 2009. The SW African volcanic rifted margin and the initiation of the Walvis Ridge, South Atlantic. *Marine Geophysical Researches, 30(3), 207-214.*

16. Fischer, M., Uenzelmann-Neben, G., Jacques, G., and Werner, R. , 2017. SO232–The Mozambique Ridge: a document of massive multistage magmatism. *In Schriftenreihe Projektträger Jülich ,114-117.*

17. Gandyukhin et al., the Report "Geological and geophysical research and assessment of the mineral resources potential of the eastern Weddell Sea", *Lomonosov, Funds of the Federal State Enterprise Scientific and Production Enterprise "PMGRE", 56th RAE, 2012.*

18. Gandyukhin et al., the Report "Geological and geophysical research and assessment of the mineral resources potential of the Antacric and its coastal seas" *Lomonosov, Funds of the Federal State Enterprise Scientific and Production Enterprise "PMGRE", 58h RAE, 2014.*

19. Geoffroy L. ,2005. Volcanic passive margins*. C. R. Geoscience. Vol. 337, 1395–1408.*

20. Gladczenko, T. P., Skogseid, J., and Eldhom, O. ,1998. Namibia volcanic margin. *Marine Geophysical Researches, 20(4), 313-341.*

21. Gohl, K. , 2008. Antarctica's continent-ocean transitions: consequences for tectonic reconstructions. In Antarctica: A Keystone in a Changing World: Proceedings of the 10th International Symposium on Antarctic Earth Sciences/Alan K. Cooper, Peter Barrett, Howard Stagg, Bryan Storey, Edmund Stump, Woody Wise, and the 10th ISAES editorial team, *Polar Resear ,29-38.*

22. Gohl, K., Uenzelmann-Neben, G., Grobys, N. ,2011. Growth and dispersal of a southeast African large igneous province, *South African Journal of Geology, 114 (3-4), 379-386.*

23. Goodlad, S. W., Martin, A. K., and Hartnady, C. J. H.,1982. Mesozoic magnetic anomalies in the southern Natal Valley. *Nature, 295(5851), 686-688.*

24. Hartnady, C. J. H., Benavraham Z. and Rogers, J. ,1992. Deep- ocean basins and submarine rises off the continental margin of south- eastern Africa*. New Geological Research.*

25. Hinz K., 1981. A hypothesis on terrestrial catastrophes. Wedges of very thick oceanward dipping layers beneath passive continental margins — their origin and paleoenvironmental significance. *Geol. Jahr., E22, 3–28.*

26. Hinz, K., and Krause W., 1982, The continental margin of Queen Maud Land/Antarctica: Seismic sequences, structural elements and geological developments, *Geol. Jahrb., E23, 17-41.*

27. Hinz, K., Neben S., Guseva Y., and Kudryavtsev G., 2004. A Compilation of Geophysical data from the Lazarev Sea and the Riiser-Larsen Sea, Antarctica, *Mar. Geophys. Res., 25, 233–245.*

28. Holbrook, W. S. and Kelemen, P. B., 1993. Large igneous province on the US Atlantic margin and implications for magmatism during continental breakup. *Nature, 364(6436), 433-436.*

29. Jokat, W., Hübscher, C., Meyer, U., Oszko, L., Schöne, T., Versteeg, W. and Miller, H., 1996. The continental margin off East Antarctica between 10 W and 30 W. *Geological Society, London, Special Publications, 108(1), 129-141.*

30. Jokat, W., Boebel, T., König, M. and Meyer, U., 2003. Timing and geometry of early Gondwana breakup. *Journal of Geophysical Research: Solid Earth, 108(B9).*

31. Kimbell, G. S., and Richards, P. C., 2008. The three-dimensional lithospheric structure of the Falkland Plateau region based on gravity modelling. *Journal of the Geological Society, 165(4), 795-806.*

32. King, E. C., 2000. The crustal structure and sedimentation of the Weddell Sea embayment: implications for Gondwana reconstructions. *Tectonophysics, 327(3), 195-212.*

33. König, M., & Jokat, W., 2006. The Mesozoic breakup of the Weddell Sea*. Journal of Geophysical Research: Solid Earth, 111(B12).*

34. Konig, 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.*

35. Koopmann, H., Brune, S., Franke, D.and Breuer, S., 2014. Linking rift propagation barriers to excess magmatism at volcanic rifted margins. *Geology, 42(12), 1071-1074.*

36. Koopmann, H., Schreckenberger, B., Franke, D., Becker, K., and Schnabel, M., 2014b. The late rifting phase and continental break-up of the southern South Atlantic: the mode and timing of volcanic rifting and formation of earliest oceanic crust. *Geological Society, London, Special Publications, 420(1), 315-340.*

37. Kristoffersen, Y., and LaBrecque, J., 1991. On the tectonic history and origin of the Northeast Georgia Rise. *Sci. Results, Vol. 114, 23-38.*

38. Kristoffersen, Y., Hofstede, C., Diez, A., Blenkner, R., Lambrecht, A., Mayer, C., and Eisen, O., 2014. Reassembling Gondwana: A new high quality constraint from vibroseis exploration of the sub-ice shelf geology of the East Antarctic continental margin. *Journal of Geophysical Research: Solid Earth, 119(12), 9171-9182.*

39. Kudryavtsev G.A., Butsenko V.V. and Kadmina I.N., 1991. Crustal section across the Western Queen Maud Land continental margin from geophysical data. *In: Abstracts of Sixth International Simposium on Antarctic Earth Sciences, Tokyo, 330-335.*

40. Kuvaas, B., & Kristoffersen, Y., 1991. The Crary Fan: a trough-mouth fan on the Weddell Sea continental margin, Antarctica. *Marine Geology, 97(3-4), 345-362.*

41. LaBrecque J.L. & Ghidella M.E., 1997. Bathymetry, depth to magnetic basement, and sediment thickness estimates from aerogeophysical data over the western Weddell Sea*, J. Geophys. Res., 102, 7929–7945.*

42. Lawver, L. A., Gahagan, L. M., and Coffin, M. F., 1992. The development of paleoseaways around Antarctica. *The Antarctic Paleoenvironment: A Perspective on Global Change: Part One, 70.*

43. Lawver, L. A., Gahagan, L. M., and Dalziel, I. W. D., 1999. Antarctica, keystone of Gondwana. *University of Texas Institute for Geophysics, Austin.*

44. Leinweber, V. T., and Jokat, W., 2012. The Jurassic history of the Africa–Antarctica corridor—new constraints from magnetic data on the conjugate continental margins. *Tectonophysics, 530, 87-101.*

45. Leitchenkov, G., Stagg, H., Gandjukhin, V., Cooper, A. K., Tanahashi, M., and O'brien, P. , 1994. Cenozoic seismic stratigraphy of Prydz Bay (Antarctica). *Terra Antartica, T. ., №. 2, 395-397.*

46. Leitchenkov, G. L., Miller H., and Zatzepin E. N., 1996. Structure and Mesozoic evolution of the eastern Weddell Sea, Antarctica: History of early Gondwana break-up, in Weddell Sea Tectonics and Gondwana Break-up, edited by B. C. Storey, E. C. King, and R. A. Livermore, *Geol. Soc. London Spec. Publ., 108, 143–154.*

47. Leitchenkov, G. L. and Masolov, V. N.,1997. Tectonic and magmatic history of the Eastern Weddell Sea region. *The Antarctic Region: Geologic Evolution and Processes, 461-466.*

48. Leitchenkov G.L. and Grikurov G., 2012. Tectonic map of Antarctica. *Comission for Geological Map of the World, Paris, 2012*

49. Le Pichon, X., Eiitreim S.L., Ludwig W.J., 1971. Sediment transport and distribution in the Argentine Basin. 1. Antarctic bottom current passage through the Falkland Fracture Zone. *Physics and chemistry of the earth. Oxford, Pergamon. v.8, 1-28.*

50. Livermore, R. A., & Woollett, R. W. , 1993. Seafloor spreading in the Weddell Sea and southwest Atlantic since the Late Cretaceous. *Earth and Planetary Science Letters, 117(3-4), 475-495.*

51. Lorenzo, J. M. and Mutter, J. C., 1988. Seismic stratigraphy and tectonic evolution of the Falkland/Malvinas Plateau. *Revista Brasileira de Geociencias, 18(2), 191-200.*

52. Menzies, M. A., Klemperer S. L., Ebinger C. J., and Baker J. , 2002. Characteristics of volcanic margins, in Volcanic Rifted Margins, *Geol. Soc. Am. Spec. Pap., vol. 362, edited by Menzies M. A. et al., 1–14.*

53. Miller, H., De Batist, M., Jokat, W., Kaul, N., Steinmetz, S., Uenzelmann-Neben, G. and Versteeg, W., 1991. Revised Interpretation of Tectonic features in the Southern Weddell Sea, Antarctica, from new seismic data, *Polarforschung 60(1), 33–38.*

54. Müller, R. D., Gohl, K., Cande, S. C., Goncharov, A., and Golynsky, A. V., 2007. Eocene to Miocene geometry of the West Antarctic rift system. *Australian Journal of Earth Sciences, 54(8), 1033-1045.*

55. Nguyen, L. C., Hall, S. A., Bird, D. E., and Ball, P. J., 2016. Reconstruction of the East Africa and Antarctica continental margins. *Journal of Geophysical Research: Solid Earth, 121(6), 4156-4179.*

56. Olesen, O., Ebbing, J., Lundin, E., Mauring, E., Skilbrei, J. R., Torsvik, T. H. and Sand, M. , 2007. An improved tectonic model for the Eocene opening of the Norwegian–Greenland Sea: Use of modern magnetic data. *Marine and Petroleum Geology, 24(1), 53-66.*

57. Planke, S., and Eldholm, O. ,1994. Seismic response and construction of seaward dipping wedges of flood basalts: Vøring volcanic margin. *Journal of Geophysical Research: Solid Earth, 99(B5), 9263-9278.*

58. Planke, S., Alvestad, E., and Eldholm, O. ,1999. Seismic characteristics of basaltic extrusive and intrusive rocks. *The Leading Edge, 18(3), 342-348.*

59. Planke S., Symonds P., Alvestad E., Skogseid J., 2000. Seismic volcanostratigraphy of large basaltic extrusive complexes on rifted margins. *Journ. Geoph. Res. Vol. 105, 19355–19351.*

60. Reeves C.V. & Estevao S.M., 2016. Insight into the Eastern Margin of Africa from a new tectonic model of the Indian Ocean. *Geological Society London Special Publications, 431, 299-322.*

61. Rogenhagen, J., & Jokat, W., 2000. The sedimentary structure in the western Weddell Sea. *Marine Geology, 168(1), 45-60.*

62. Rogenhagen J., Jokat W., Hinz K. and Kristoffersen Y., 2004. Improved seismic stratigraphy of the Mesozoic Weddell Sea. *Mar. Geophys. Res., 25, 265–282.*

63. Sengor, A. M., and Burke, K. , 1978. Relative timing of rifting and volcanism on Earth and its tectonic implications. *Geophysical Research Letters, 5(6), 419-421.*

64. Skogseid, J. and Eldholm, O., 1987. Early Cenozoic crust at the Norwegian continental margin and the conjugate Jan Mayen Ridge. *Journal of Geophysical Research: Solid Earth, 92(B11), 11471-11491.*

65. Symonds, P. A., Planke, S., Frey, Ø. and Skogseid, J. 1998.Volcanic development of the Western Australian continental margin and its implications for basin development. *The Sedimentary Basins of Western Australia 2: Proceedings of Petroleum Exploration Society of Australia Symposium, Perth, 33 – 54.*

66. Tsikalas, F., Eldholm, O., and Faleide, J. I. ,2005. Crustal structure of the Lofoten–Vesterålen continental margin, off Norway. *Tectonophysics, 404(3), 151-174.*

67. Uenzelmann-Neben, G., 2014. The Expedition of the Research Vessel "Sonne" to the Mozambique Ridge in 2014 (So 232), *in Reports on Polar and Marine Research.*

68. Vail, P. R., Mitchum Jr, R. M., and Thompson III, S. ,1977. Seismic stratigraphy and global changes of sea level: Part 3. Relative changes of sea level from Coastal Onlap: section 2. *Application of seismic reflection Configuration to Stratigrapic Interpretation. 63-81.*

69. White R., McKenzie D.,1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journ. Geoph. Res. Vol. 94, 7685–7729.*

Acknowledgement

First of all, I would like to express my gratitude to my scientific advisors- Dr German Leonidovich Leitchenkov for the great help, continuous feedback and guidance through this project; and to Dr Sascha Brune for his valuable remarks and comments.

I am incredibly grateful to all lecturers of the POMOR master program from the Saint Petersburg State University and from the University of Potsdam, their lectures were truly inspiring and motivating.

I am grateful to the POMOR management and administration, particularly to Dr Heidi Kassens, Ksenia, Nadezhda and Victoria for creating warm atmosphere and for providing constant support.

Thanks to all fellow students from our spectacular group, it was such a pleasure to know you all and I hope we will continue our way in this amazing field of science.

I owe special thanks to my family for their support, without them it would not be possible; and to all my friends, especially to Anastasia and Panagiotis, who supported and encouraged me during the whole work.

Statement of originality

Herewith I, Tatiana Sitnikova, declare that I wrote the thesis independently and did not use any other resources than those named in the bibliography, and, in particular, did not use any internet resources than those named in the bibliography. The master thesis has not been used previously as part of an examination. The master thesis has not been previously published.