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INTEGRATED GEOPHYSICAL ANALYSIS OVER BATHYMETRISTS SEAMOUNTS AND THE SIERRA LEONE RISE

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INTEGRATED GEOPHYSICAL ANALYSIS OVER BATHYMETRISTS SEAMOUNTS AND THE SIERRA LEONE RISE

An Undergraduate Thesis

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By

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Abstract

The Bathymetrists Seamounts (BSM) are located northeast of the Sierra Leone Rise in the Atlantic Ocean. The northern seamounts have a southwest to northeast trend which is contrary to the current eastward motion of the African tectonic plate where they reside. The geological history and crustal structures of these features are poorly understood. The goal of this study is to integrate multiple geophysical data to better understand the crustal architecture and tectonic history of the BSM.

The seismic refraction study from Jones et al. (2015) was used as the baseline for isostatic modeling. This dataset suggested the presence of magmatic underplating beneath the Sierra Leone Rise but failed to reveal crustal features beneath the Bathymetrists Seamounts. Isostatic modeling was developed to find possible constraints on the crustal architecture beneath the BSM. This was achieved by balancing pressures underneath the SLR and BSM crustal blocks, as well as the other locations studied by Jones et al. (2015). The isostatic model suggested a thick crust with magmatic underplating beneath the BSM, triggering a new hypothesis about the BSM and SLR crustal blocks being formed at the same time.

The two-dimensional model was developed by integrating seismic, gravity, and magnetic data to study the crustal architecture beneath the research area further. The model confirmed the presence of magmatic underplating beneath the BSM as it was essential to satisfy the gravity field. Magnetic data were modeled in accordance with polarity reversals based on published ages of the African oceanic crust. The crust that the Bathymetrists Seamounts reside on was formed during the Cretaceous Magnetic Quiet Zone (121-84 Ma) - a period of normal magnetic polarity, so no reversals were expected. However, a developed two-dimensional model requires multiple reversals over the BSM block to match the observed magnetic data, suggesting that the seamounts are younger than the crust they reside on.

The integration of different geophysical datasets increases the confidence in derived crustal architectures of the Bathymetrists Seamounts and Sierra Leone Rise. The results suggest the presence of a left-lateral fault between these blocks trending in the same direction as seamounts. The hypothesized fault was active at the time when the seamounts were formed and

resulted in ~ 100 km offset between SLR and BSM crustal blocks. Further investigations are required to confirm the presence of this fault.

Key Words: Bathymetrists Seamounts, Sierra Leone Rise, Mid-Atlantic Ocean, Tectonic structures, Isostatic modeling, 2-Dimensional modeling, Integrated geophysical modeling

Dedication

I would like to acknowledge and dedicate this thesis to everyone who contributed and provided support for this research. I am grateful to the UCARE Program for providing funding throughout my research. Many thanks go to the Department of Earth and Atmospheric Sciences at the University of Nebraska-Lincoln and the Geophysics Team. I would like to acknowledge Dr. Hübscher, from the University of Hamburg, Germany, for providing key data and the incentive to work on this research. Lastly, I would like to dedicate this thesis to Dr. Filina, who was always there from the very beginning, presenting me with this opportunity and providing support inside and outside of this research.

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1. Introduction

The Bathymetrists Seamounts are located in the central Atlantic Ocean northeast of the Sierra Leone Rise. The southern portion of the seamounts has a west to east trend following the movement of the African tectonic plate, while the northern one has a southwest to northeast trend that contradicts the direction of the tectonic plate they reside on. The purpose of this study is to determine the crustal structure of the BSM block in order to understand the origin of seamounts and their relationship with the adjacent Sierra Leone Rise.

The major tectonic structures of the central Atlantic Ocean are shown in **Figure 1-1.** The Mid-Atlantic ridge is an actively spreading center where new oceanic crust is being formed. The spreading rate is averaged 21 to 22 cm per year (Hussenoeder et al., 2002). The spreading direction is perpendicular to the Mid-Atlantic ridge (white arrows in **Figure 1-1**), where the African and South American plates are pushed away from each other in the east and west directions respectively. Other relevant tectonic features include the Sierra Leone Rise and Cearà Rise (red outlines in **Figure 1-1**), as well as the Sierra Leone Basin further discussed in **Chapter 2**.

This research intends to study the crustal structures and tectonic origin of the Bathymetrists Seamounts (yellow outline in **Figure 1-1**). This study has three primary objectives. The first one is to perform a literature review of the study area and conjugate features, as well as gather geophysical data from the public domain. The key findings from that objective are described in **Chapters 2** and **3**. The second objective is to develop an isostatic model for the seamounts and Sierra Leone Rise to study their crustal architectures and understand the relationship between these two tectonic blocks. The last objective is to develop a two-dimensional model of the study area that integrates potential fields (gravity and magnetic) with the isostatic model leading to a hypothesis about the origin and relative age of the BSM. Methodologies for isostatic and two-dimensional modeling are described in **Chapter 4**, while the major findings are analyzed in **Chapter 5** and the resultant hypothesis is formulated in **Chapter 6**.

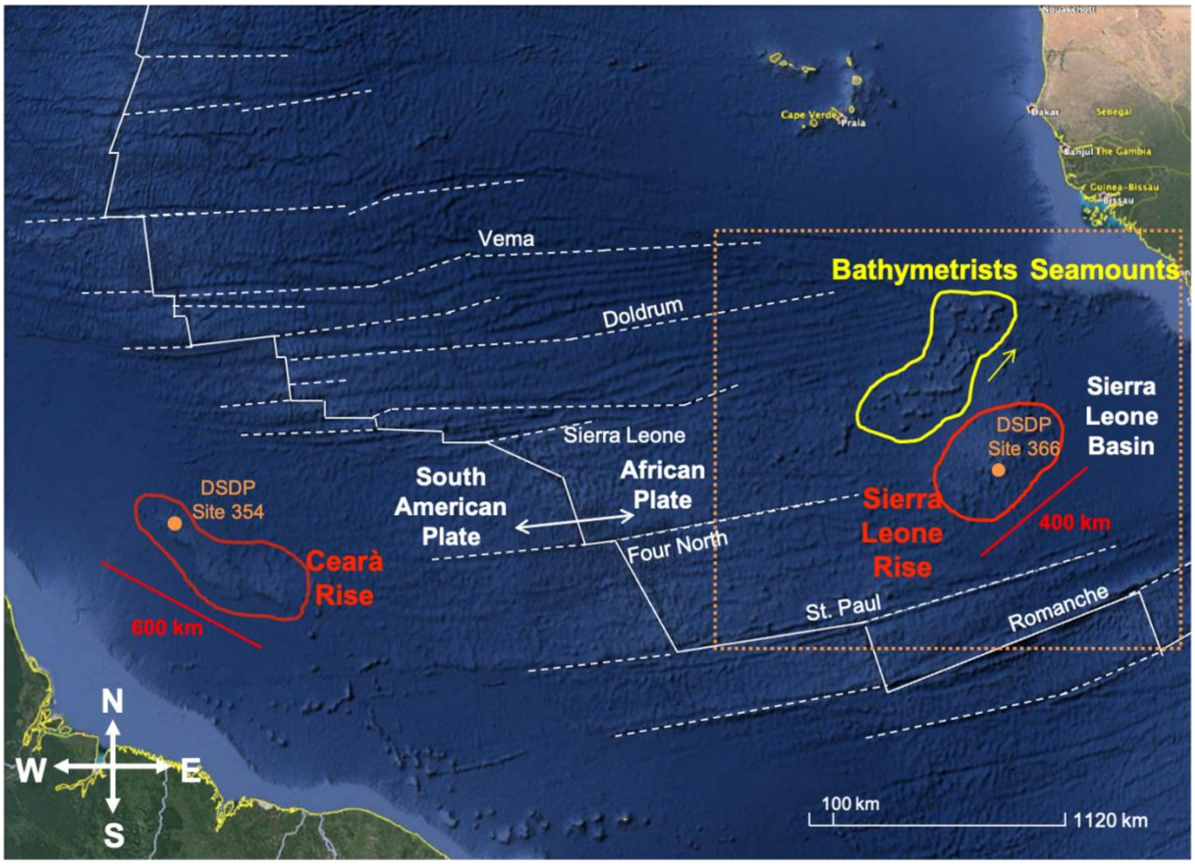


Figure 1-1. Screenshot of the Central Atlantic Ocean from Google Earth. The solid white line shows the Mid-Atlantic Ridge. The transform faults extending from the ridge are shown with the dashed white lines. Two conjugate features – Sierra Leone Rise on the African plate and Cearà Rise on the South American plate are outlined in red. Note the 200 km mismatch in length of the features. The study area is shown within the orange dashed rectangle. The Bathymetrists Seamounts are outlined in yellow with a yellow arrow suggesting the northern segment's directional trend for the northern part of the seamounts, contradicting the eastward movement of the African tectonic plate shown with the white arrow. The DSDP drilling locations 354 in the Cearà Rise and 366 in the Sierra Leone Rise are shown with orange dots.

2. Geological Background

2.1. Sierra Leone Rise, Sierra Leone Basin, and Cearà Rise

The Sierra Leone Rise is a bathymetric high on the African tectonic plate. Its conjugate feature, the Cearà Rise, is located on the South American plate (red outlines in **Figure 1-1**). The Sierra Leone Rise and the Cearà Rise originated from a mantle plume that was active beneath the spreading center in the Atlantic Ocean approximately 80 Ma (Hékinian et al., 1978). The plume added magmatic material and thickened the crust in both regions (Kumar et al., 1979). According to the seismic refraction experiment of Jones et al. (2015) discussed in **Section 2.3**, up to 6.2 km of magmatic material was added to the Sierra Leone Rise.

Through time, the Cearà and Sierra Leone Rises were pushed away from each other by the consequent oceanic spreading. The age of these structures was determined from drilling over the Cearà Rise which reached the basement (Perch-Nielsen, et al., 1977). The well on site 354 penetrated the basaltic basement of the upper Cretaceous Period, dating back to about 80 Ma (Kumar et al., 1979). The oldest volcanic rocks (basalt) found were dated as Early Maastrichtian (72.1 - 66 Ma) and the youngest sediments were of the Late Pleistocene age (0.13 to 0.012 Ma).

In contrast, drilling over the Sierra Leone Rise penetrated sediments of similar age, although the basement was not reached (Lancelot et al., 1978). The drilling over Site 366 provided detailed information on the composition, lithologies and age of the Sierra Leone Rise sedimentary column (**Figure 2-1**). The oldest material found at the bottom of the well was dated as Late Cretaceous (Maastrichtian), while the age of the youngest sediments was Quaternary (Pleistocene - 2.58 to 0.012 Ma). The depth of the well reached 850.5 meters and did not penetrate the basement, resulting in a poor understanding of the nature and age of the crust. Comparing these findings to the drilling of Site 354 over the Cearà Rise, the oldest rocks are dated to be around the same age. Magnetic data from Müller et al. (2018) also suggest the age of the oceanic lithosphere beneath the SLR is ~80 Ma, consistent with data from the drilling performed in sites at both the Cearà Rise and Sierra Leone Rise.

Since both the Sierra Leone Rise and Cearà Rise are conjugate features, it is assumed they originated at the same time and, therefore, will be approximately the same age. However, the overall length of the Cearà Rise is approximately 600 km, while the Sierra Leone Rise is only

~ 400 km, as shown in **Figure 1-1**. This 200 km difference contributes to the many unknowns about the study area.

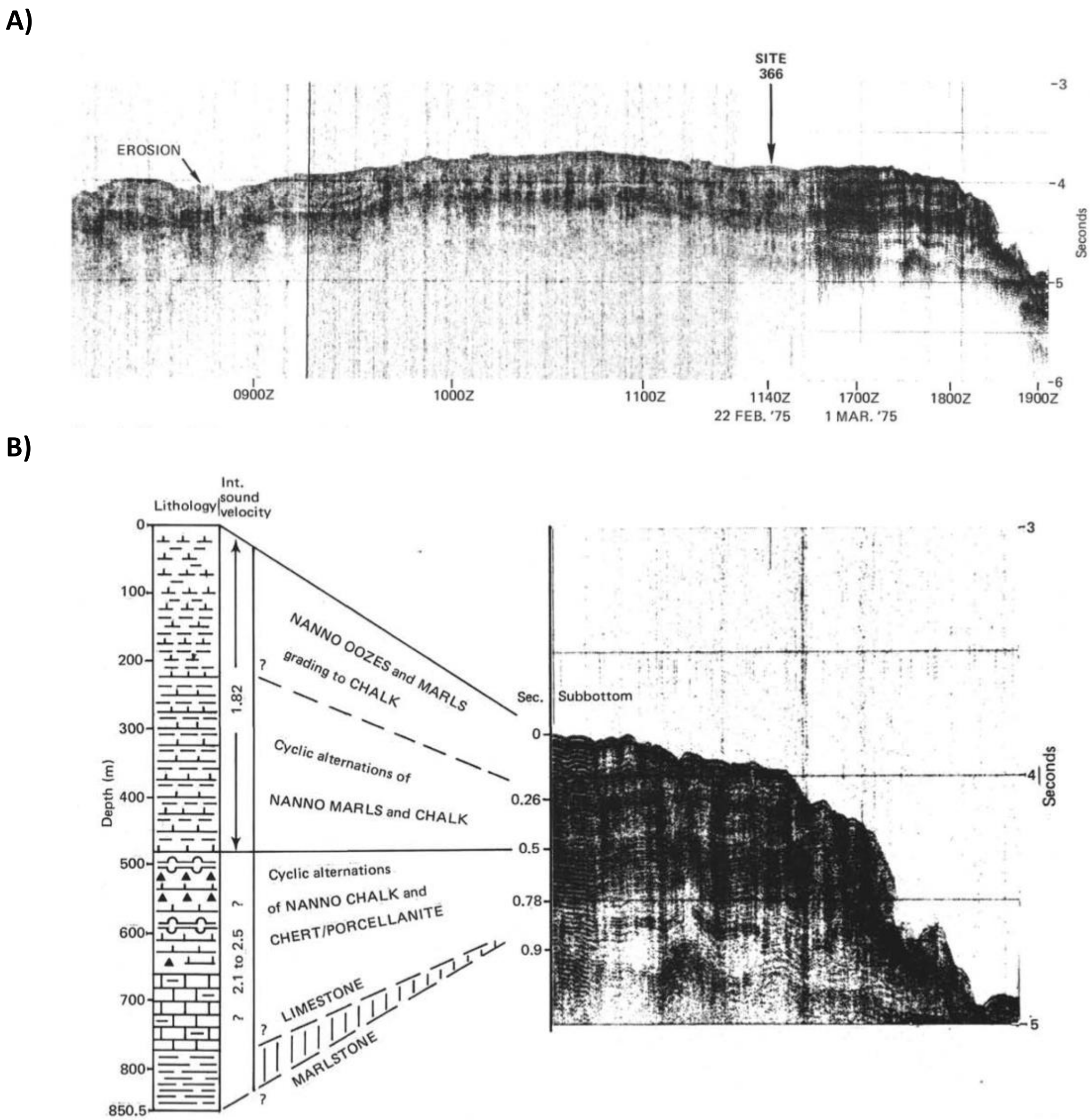


Figure 2-1. A) The reflection profile over the Sierra Leone Rise with the location of the DSDP Site 366 site. **B)** Correlation of seismic profile and drilling results at Site 366.

(*Figures taken from Lancelot et al., 1978*).

The oceanic crust of the Sierra Leone Basin formed before the Sierra Leone Rise and Cearà Rise structures approximately 90 Ma (Müller et al., 2008). The seismic refraction studies of Jones et al. (2015) show that the Sierra Leone Basin has a normal oceanic crust (up to 8 km thick) without any magmatic underplating.

2.2. Bathymetrists Seamounts

The Bathymetrists Seamounts are located on the African tectonic plate, north of the Sierra Leone Rise, between 6° N and 9° N (**Figure 2-2**). The seamounts have two distinct directional patterns, where the southern portion has an apparent west to east trend, while the northern part is aligned in the southwest to northeast direction. The trend of the northern Bathymetrists Seamounts contradicts the current eastward spreading direction of the African plate (white arrows in **Figure 1-1**). The cause for this pattern and its relationship to the origin of the seamounts remains unknown.

The magnetic data from Müller et al. (2008) (**Figure 2-3**) shows the age of the oceanic lithosphere. The estimated ages for the study area range from 60 to 90 Ma. No drilling has been done in the seamounts, and their age has not yet been determined. However, dredging of the seafloor over the seamounts suggested the much younger age of these rocks ranging from early Eocene (47.8 - 56 Ma; Peyve and Skolotnev, 2009) to middle Eocene (~ 40 to 46 Ma; Skolotnev et al., 2017). The approximate age of the Bathymetrists Seamounts falls outside of the range suggested by magnetic data, implying that the seamounts developed well after the oceanic lithosphere of the African tectonic plate was formed. Furthermore, the BSM is suggested to be located over crust that formed 105 to 75 Ma (Müller et al., 2008).

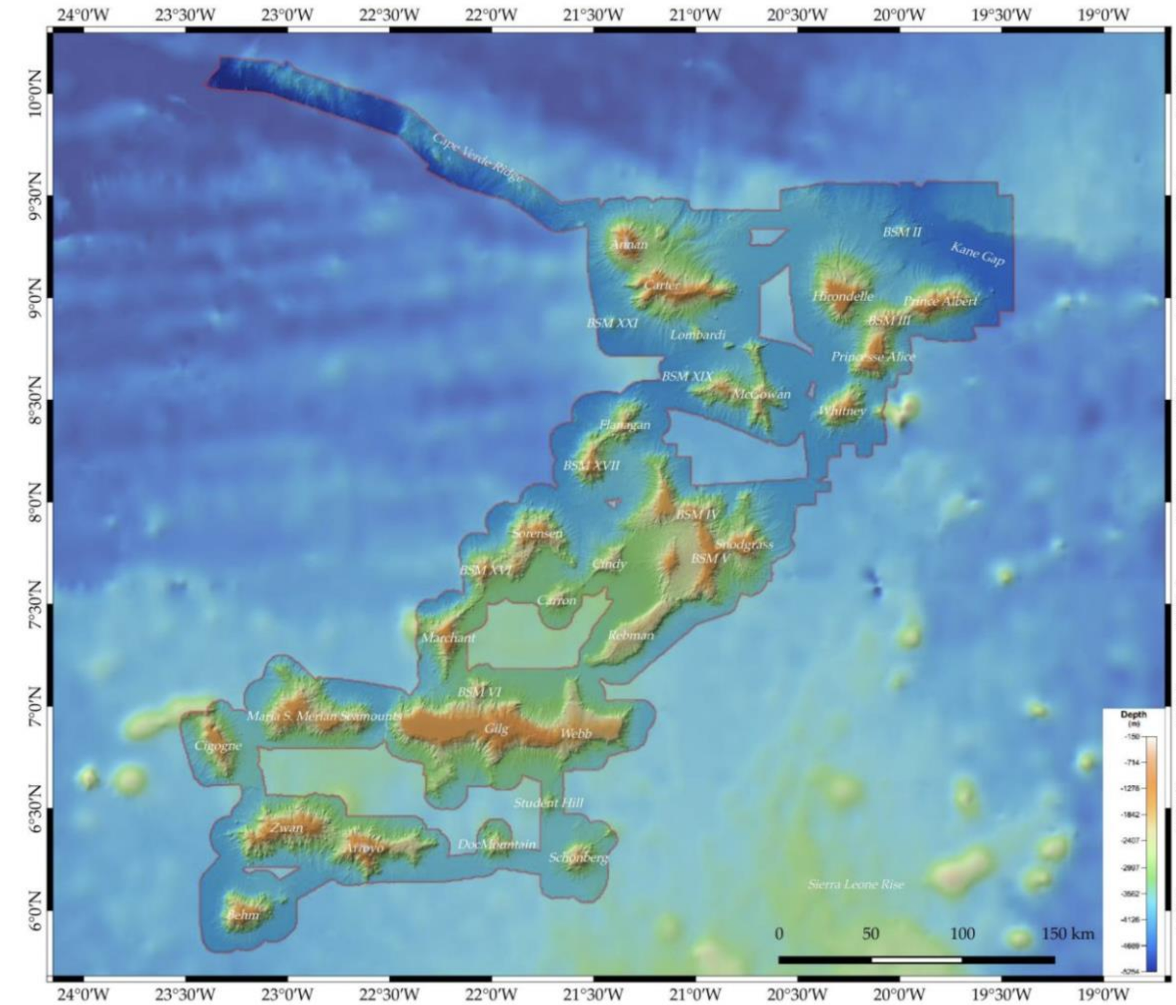
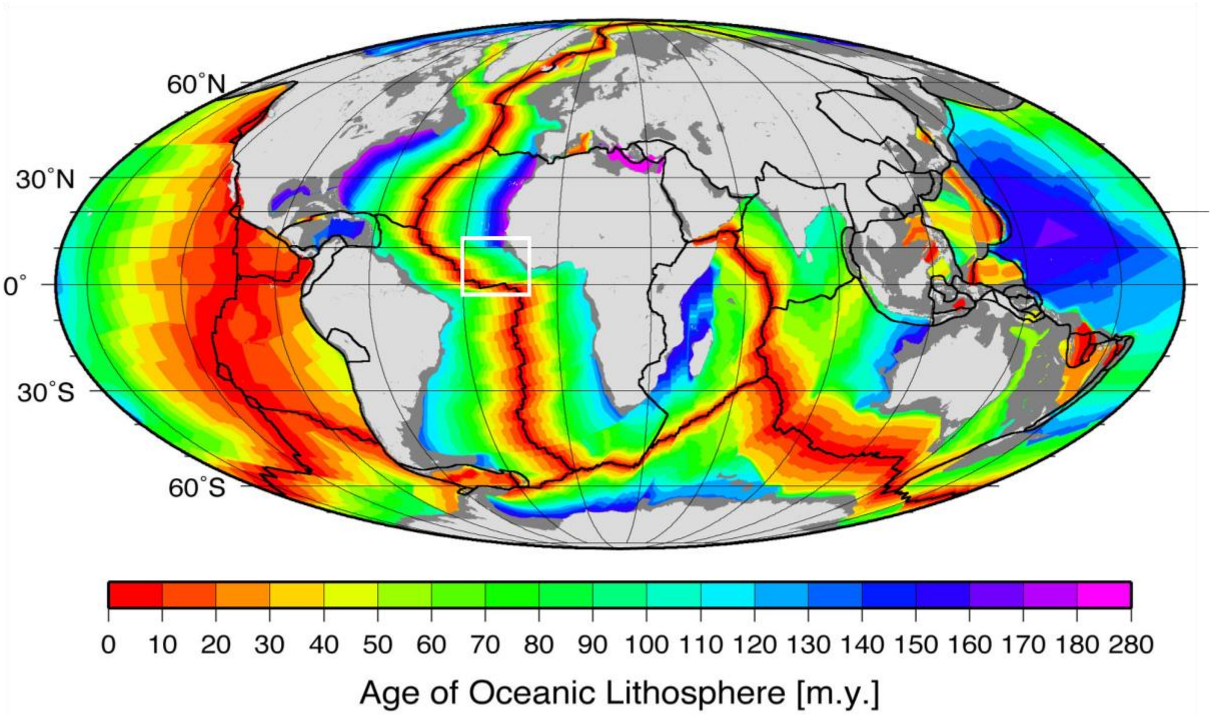


Figure 2-2. Bathymetry map of the seamounts north of the Sierra Leone Rise. The southern part presents a horizontal E-W trend, while the northern part shows a diagonal SW-NE trend. (*Figure taken from Hübscher et al., 2019)*.

A)



B)

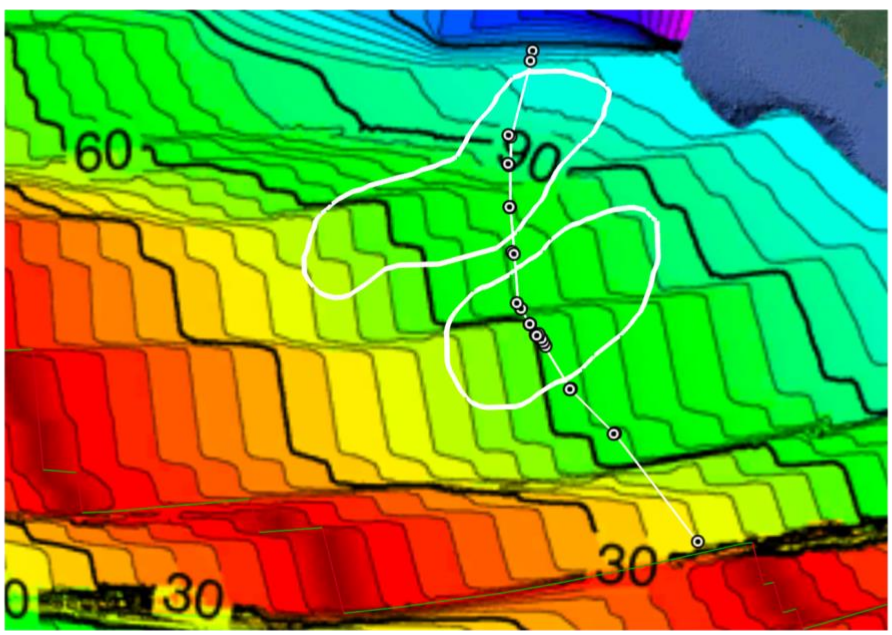


Figure 2-3. A) Age of the oceanic lithosphere based on isochrones from magnetic data (*Müller et al., 2018*). The approximated location of the study area is outlined in a white box. **B)** Crustal ages of the BSM and Sierra Leone Rise (outlined in white); isochrons interval is 5 Ma. The northern region of the BSM falls between 75 and 105 Ma.

(*Figure adapted from Müller et al., 2018)*

The southwest to northeast trend associated with the seamounts remains poorly understood. There are two competing hypotheses for the formation of the BSM (Hubscher et al. 2019). The first one relates to the mantle plume that was active during the Early Eocene (56 to 47.8 Ma), while the second one relates to small-scale sublithospheric convection (SSC) related to decompressional melting.

Dredging over the northeastern part of the BSM (Carter Seamount) recovered volcanic rocks of the Early Eocene age (56 to 47.8 Ma), which was interpreted by Payve and Skolotnev (2009) as evidence for “strong mantle pulse” responsible for the formation of the seamounts. This is consistent with the mantle-plume hypothesis proposed by Schilling et al. (1994) based on geochemical analysis of dredged volcanic rocks from 65 sampling stations for a 1600-km-long profile. This Schilling’s study reveals the presence of “two mixing zones in the mantle that are isotopically distinct”, with the St. Paul transform fault system being established as the boundary between the two zones. The zone to the north is suggested to have been affected by a plume that was active from 75 to 48 Ma, while in contrast, the southern zone (south of the St. Paul transform fault system) was sourced by “a depleted asthenosphere unpolluted plume” (Schilling 1994).

Alternatively, a non-hotspot related origin for BSM was proposed by Ballmer et al. (2007) based on numerical modeling. This model assumes the presence of small-scale sublithospheric convection that results in volcanism “along lineaments aligned with plate motion and to span seafloor ages of 25 to 50 Myr” (Ballmer et al. 2007). This model was adapted by Schade (2018) as illustrated in **Figure 2-4**, suggesting that SSC initiated beneath the Sierra Leone Rise and resulted from a difference in lithospheric thickness between the BSM and the SLR (will be discussed further in **Section 2.3)**. However, this sub-lithospheric convection hypothesis requires a thin crust beneath the Bathymetrists Seamounts.

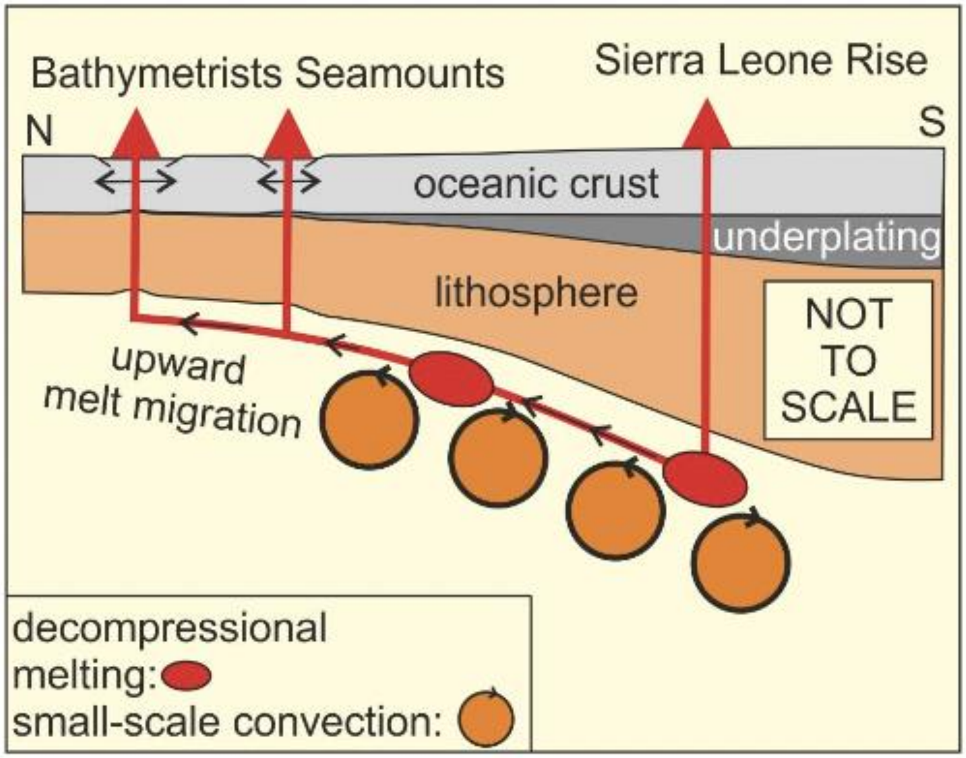


Figure 2-4. Hypothesis proposed by Schade (2018) builds upon the model of Ballmer et al. (2007) and suggests that sub-lithospheric convection beneath the Sierra Leone Rise drives volcanism responsible for formation of the Bathymetrists Seamounts.

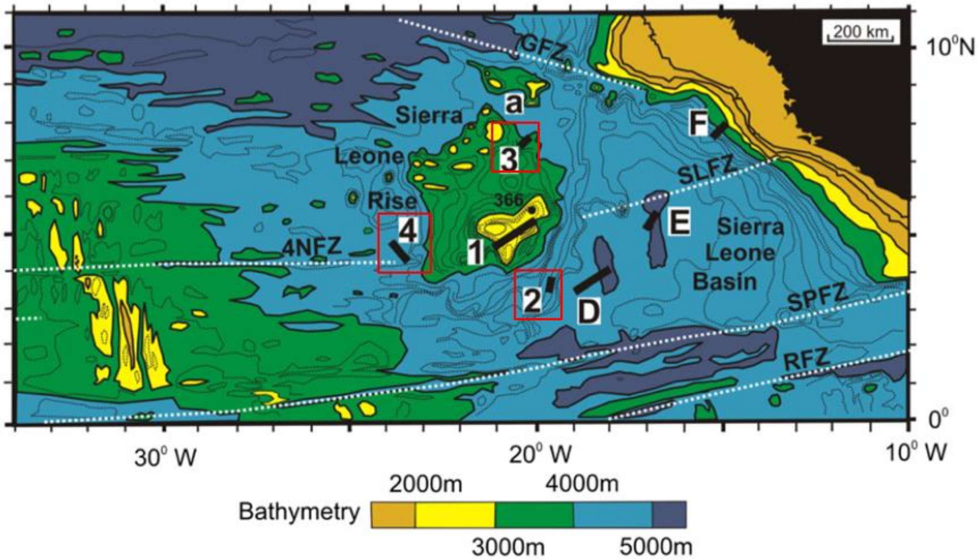
Figure taken from Hübscher et al. (2019).

2.3. Crustal architecture of BSM and SLR from seismic refraction data

This research was based on the refraction experiment of Jones et al. (2015) shown in **Figure 2-5**. The study focuses on crustal structures beneath the Sierra Leone Rise, including magmatic underplating. The thickness of crustal layers beneath the Sierra Leone Rise and Sierra Leone Basin were determined using a seismic refraction experiment. Seismic refraction surveying is based on generating an acoustic wave that propagates through the subsurface and gets reflected and refracted from major structural boundaries. The analysis of recorded seismic waves allows mapping the depths of those structures (Lillie, 1999). The seismic refraction surveying of Jones et al. (2015) allowed to map the depths of subsurface structures, such as the base of the sedimentary layer and the boundary between upper and lower oceanic crustal layers. These can be observed in **Figure 2-5 A** (locations 1, 2, 3, 4 over the Sierra Leone Rise, and D, E, F over the Sierra Leone Basin). In addition, the magmatic underplating under the Sierra Leone Rise was determined in this refraction experiment (**Figure 2-5 B**). The values within the columns in **Figure 2-5 B** represent seismic wave velocities pertaining to the lithology of each layer.

The contact between the crust and the mantle, the Moho boundary, is deeper under the Sierra Leone Rise block due to the presence of magmatic underplating and was successfully mapped in the refraction experiment beneath that block (location 1 in **Figure 2-5**). However, the crust-mantle boundary (Moho) was not mapped beneath lines 2, 3, and 4. The crust beneath the Bathymetrists Seamounts was not penetrated in this experiment either, the closest location is line 3 and did not map Moho. Therefore, the depth to Moho and overall crustal thickness remained unknown beneath the Bathymetrists Seamounts.

A)



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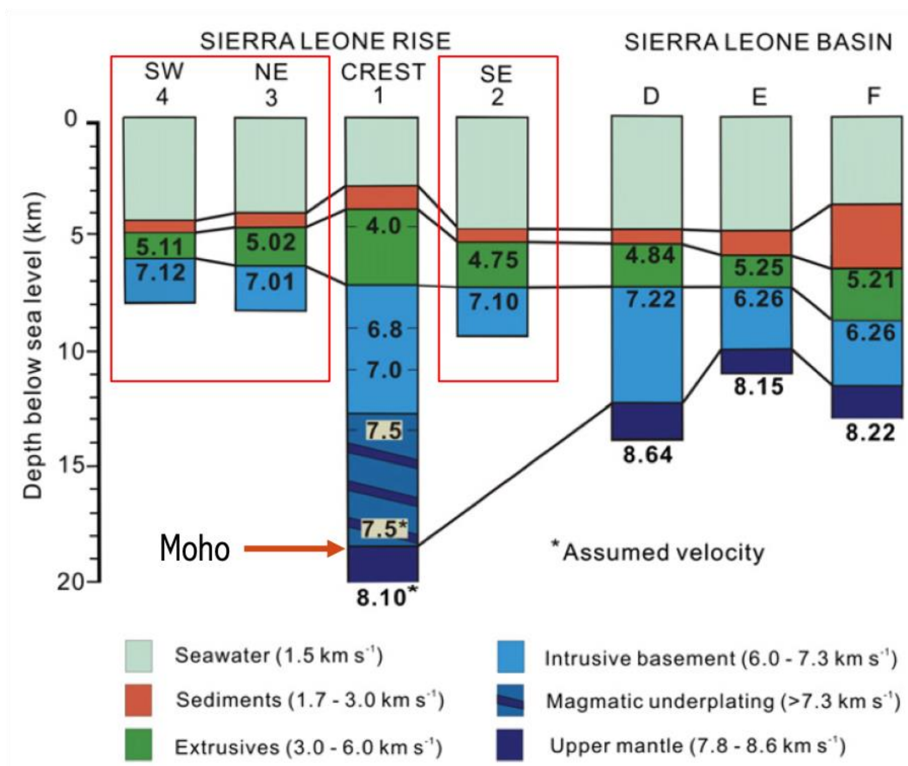


Figure 2-5. A) The location of seismic refractions from Jones et al. (2015); the red boxes indicate the locations that failed to map Moho. **B)** The resultant crustal structures and seismic velocities for each layer. Similarly, those that failed to reach Moho are outlined in red.

(Figure modified from Jones et al., 2015)

3. Geophysical Data

3.1. Bathymetry

Bathymetry data extracted from Smith et al. (1997) was used for this study to develop a bathymetry map over the study area using Geosoft software (**Figure 3-1**). This dataset was used to develop both isostatic and 2-D models by defining the layer of water above the sediment surface. Transform faults can be identified well in the bathymetry map as contrasts between high and low bathymetry values in the northwest area of the map, as well as St. Paul and Romanche transform faults on the south of the map.

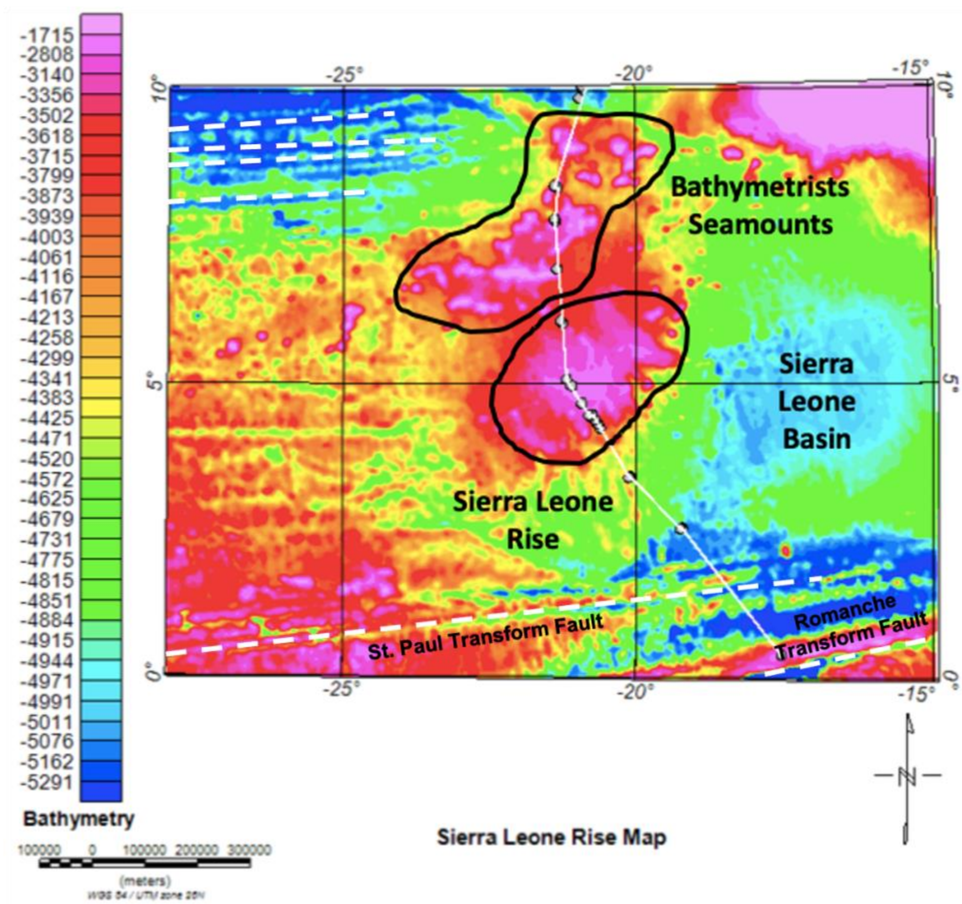


Figure 3-1. Bathymetry map data from Smith et al. (1997) gridded with sampling interval of 2 km. The Bathymetrists Seamounts and the Sierra Leone Rise are outlined in black. The seismic profile from the expedition V2206 (Ewing, 1966) is shown in white. Transform faults are outlined in a white dashed line, with major transform faults labeled.

3.2. Gravity Field

Free-Air gravity data from Sandwell et al. (2014) were used to compose a Free-Air gravity map (**Figure 3-2**). The Bouguer correction (**Figure 3-3**) was then computed to derive the Bouguer anomaly (**Figure 3-4**) over the study area. Free-air gravity data resembles a bathymetry map. This is because the Free-Air gravity represents the cumulative signal from all subsurface layers. Seawater is the top layer (I.e., the shallowest one), thus it produces the strongest gravity signal that masks everything else beneath it. The deeper sources, such as basement and Moho, are less pronounced in the Free-Air gravity anomaly. Since the thickness of seawater (i.e., bathymetry) is known (**Figure 3-1**), the gravity effect due to bathymetry can be removed from the Free-Air

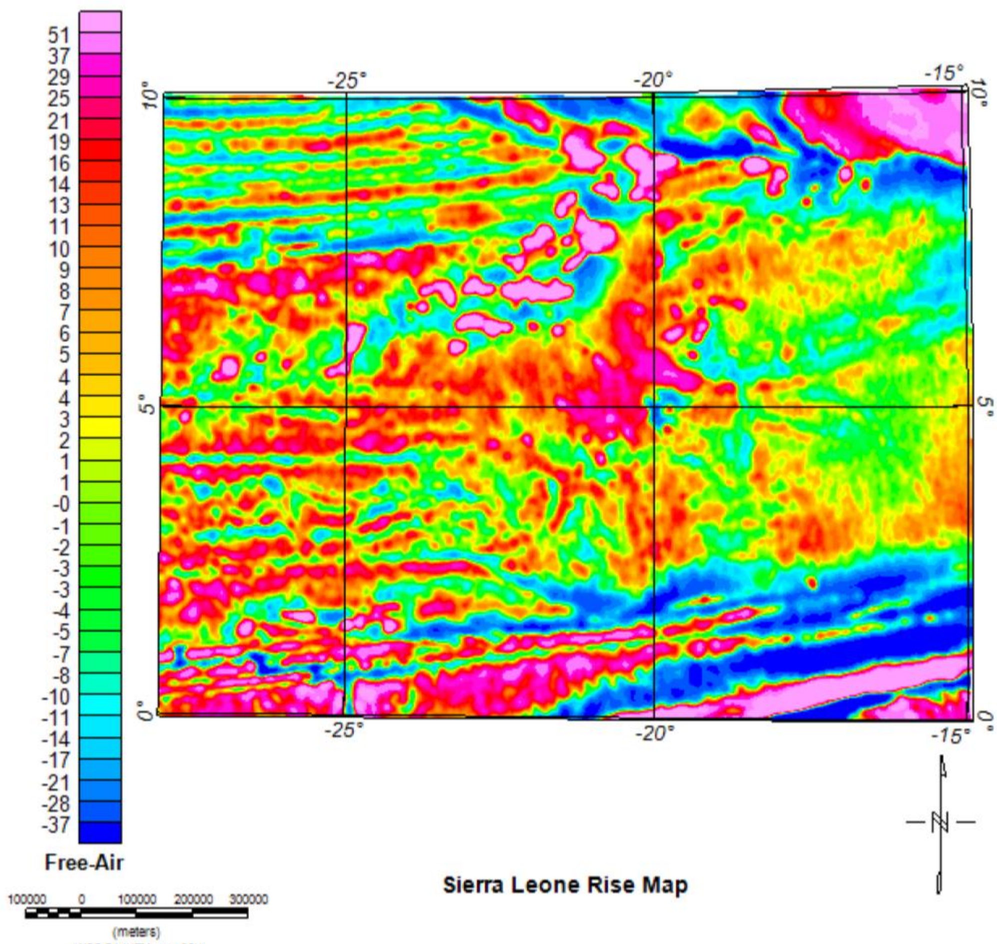
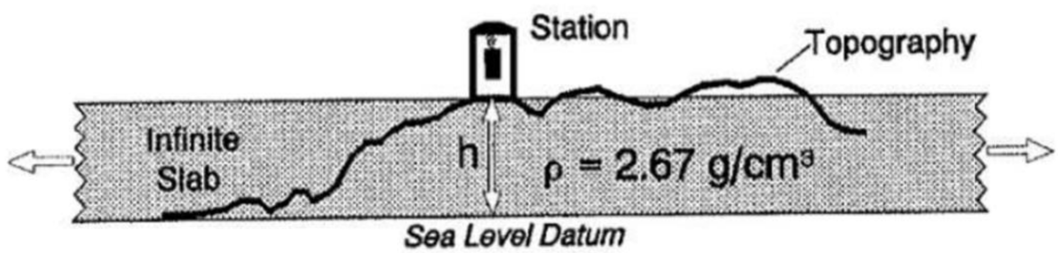


Figure 3-2. Free-Air gravity map over the study area from Sandwell et al. (2014). The Bathymetrists Seamounts are associates with the highest Free-Air gravity values.

gravity data. This is called Bouguer correction (**Figure 3-3**) and results in the Bouguer gravity anomaly map (**Figure 3-4**). The Bouguer map represents the gravity signal of everything below the sea bottom, showing high anomalies when the crust is thin (due to a high-density mantle being shallower), and low signals when the thicker crust is present (Lille, 1999).

A)



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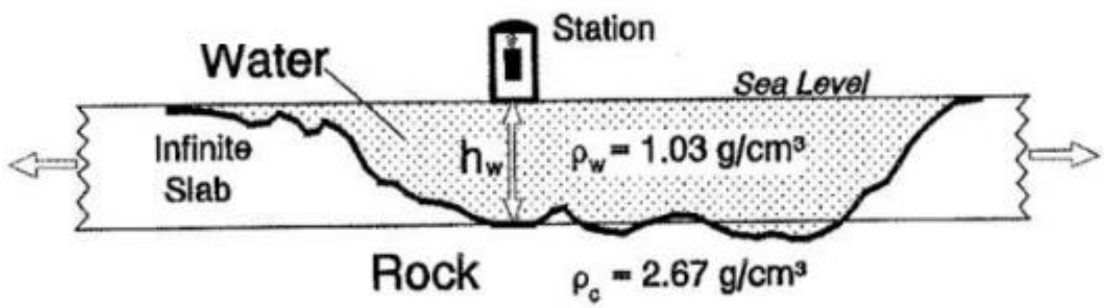

Figure 3-3. Bouguer gravity correction explained with a diagram. Difference between the value of h when measuring data on land **(A)**, and at sea **(B)**.
(Figure taken from Lillie, 1999).

The Bouguer correction was computed using bathymetry data from Smith et al. (1997), and an assumed Bouguer density contrast of -1 g/cc (density of water used as 1.0 g/cc and assumed density of the sediments at the seafloor was 2 g/cc). The Bouguer gravity correction equation is:

$$BC = 2\pi\Delta\rho G h \qquad \textbf{[1]}$$

In this equation BC is Bouguer correction, $\Delta\rho$ is density contrast, G is gravity constant, and h is the thickness (on land, it would be slab thickness, over the sea it would be bathymetry as is shown in **Figure 3-3**).

Once the Bouguer correction is estimated, Bouguer Anomaly can be calculated as follows:

$$g_{BA} = g_{FA} - BC \qquad \textbf{[2]}$$

For this equation, g_{BA} is Bouguer Anomaly, g_{FA} is Free-Air gravity anomaly, and BC is Bouguer correction (**equation [1]**).

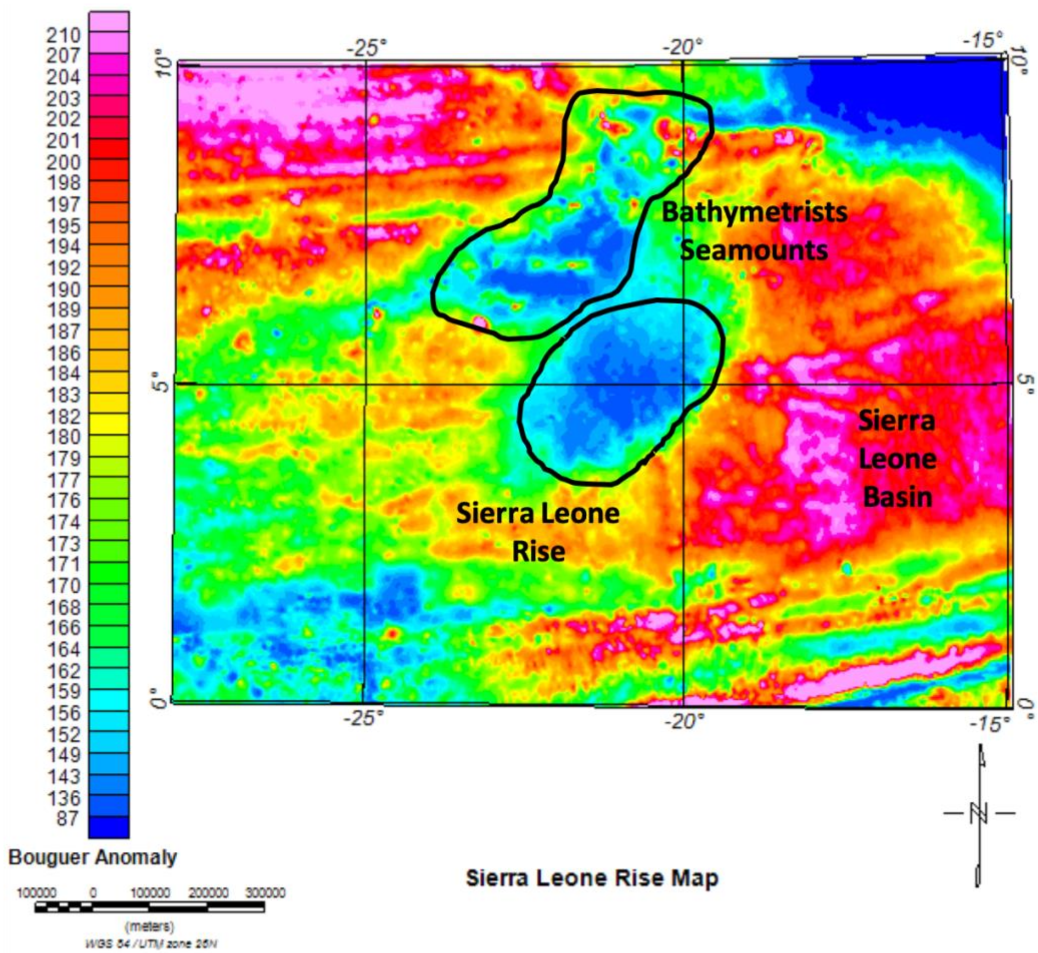

Figure 3-4. Bouguer gravity anomaly map over the study area (Sierra Leone Rise and Bathymetrists Seamounts). The black outlines show the Bathymetrists Seamounts to the north and the Sierra Leone Rise. Free-Air gravity data from Sandwell et al. (2014) was reduced using a density contrast of -1 g/cc.

The Bouguer anomaly map (**Figure 3-4**) reflects variations in the crustal thickness of the region. The evident gravity highs correlate with the relatively thin oceanic crust of the Sierra Leone Basin and of the Atlantic Ocean. In contrast, the thick crust of the Sierra Leone Rise corresponds with the gravity low, which has approximately 6.2 km of the accreted magmatic material from the mantle plume that was active during the formation of this feature about 80 Ma (Jones et al., 2015; **Figure 2-5**). This process is also called magmatic underplating. Noticeably, both the Sierra Leone Rise and Bathymetrists Seamounts correlate with a pronounced gravity low, suggesting that both crustal blocks have similarly thick crust. Like the bathymetry map, both Free-Air and Bouguer gravity maps show pronounced transform faults, which can be observed in trends from east to west and parallel to each other.

3.3. Magnetic Field

Magnetic data from Meyer et al. (2017) were used to develop a total magnetic intensity map over the study area (**Figure 3-5**). As observed in **Figure 2-3 B** the Bathymetrists Seamounts are located over crust that originated between 75 and 105 Ma. During the Cretaceous Magnetic Quiet Zone, a period between 84 and 124 Ma, there were no polarity reversals (Walker et al. 2018). Therefore, part of the Bathymetrists Seamounts located over crust during this time would be expected to have normal magnetic polarity.

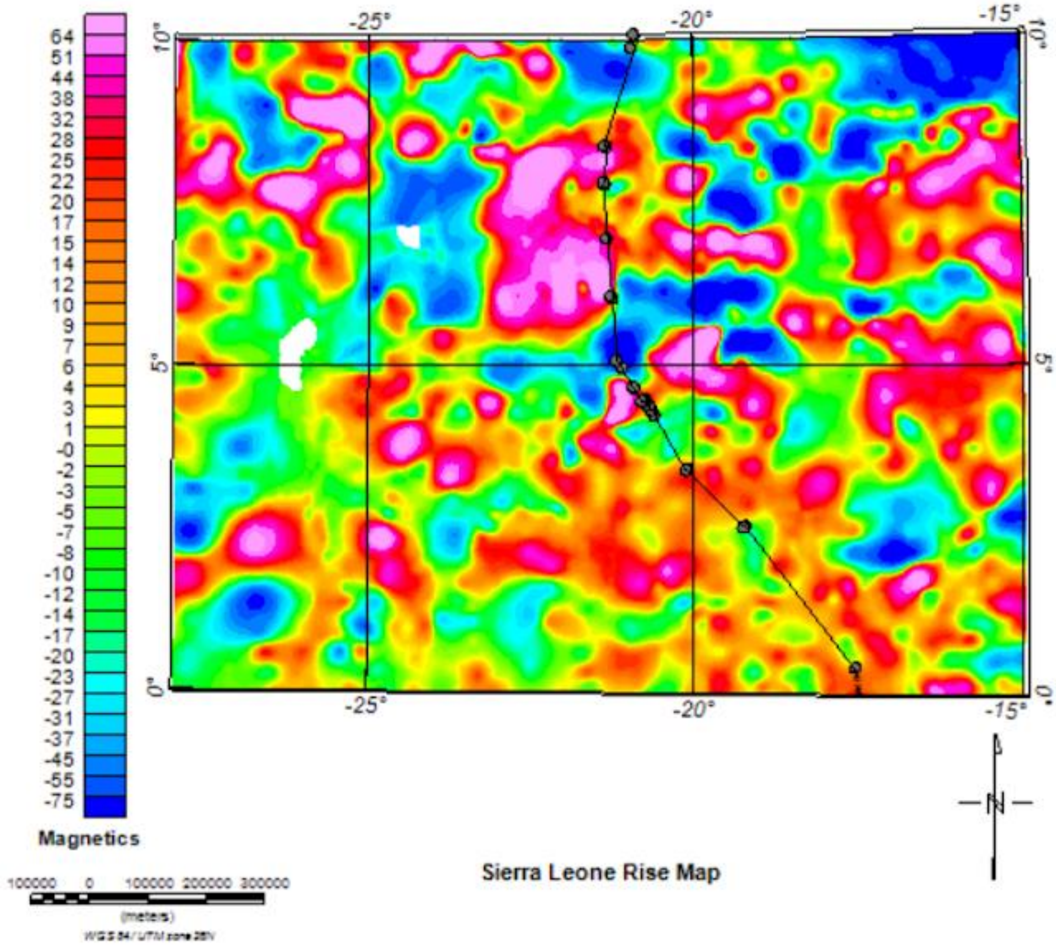

Figure 3-5. Total magnetic intensity map over the Sierra Leone Rise and Bathymetrists Seamounts. The path outlined in a black line corresponds to part of the path taken during expedition V2206.

3.4. Seismic

A vintage seismic reflection profile from expedition V2206 (Ewing, 1966) was used in this study. The images for lines 73 to 62 from that expedition were stitched together as shown in **Figure 3-6**. This profile crosses the study area as illustrated in **Figure 3-1**. The total length of Lines 73 to 62 from this expedition is 1160 km. The 2-way travel time images have 1 second interval marks. This seismic reflection profile served as a framework during constructing the 2-D model, as bathymetry and the sedimentary layers over the basement could be more accurately determined in that seismic image.

Throughout the seismic line in **Figure 3-6**, the Bathymetrists Seamounts can be observed (outlined in the blue box). Between the seamounts and Sierra Leone Rise, an interesting feature was noted (enclosed in the red circle) which seems to show characteristics of a fault. To further make this analysis, the image of the northern part of the St. Paul transform fault system can be evaluated (shown with the purple box). The structures outlined by the red circle appear to have the same characteristics as the northern part of the St. Paul transform fault system.

This seismic image was compared to the drilling from Site 366 over the Sierra Leone Rise (**Figure 2-1 B**) to correlate the different sedimentary layers. This allowed to determine the variations in sediment depositions, such as nano oozes and marls grading to chalk at the top, followed by cyclic alternations of nano marls and chalk, and at the bottom of the sediment cyclic alternations of nano chalk and chert (Lancelot et al., 1978).

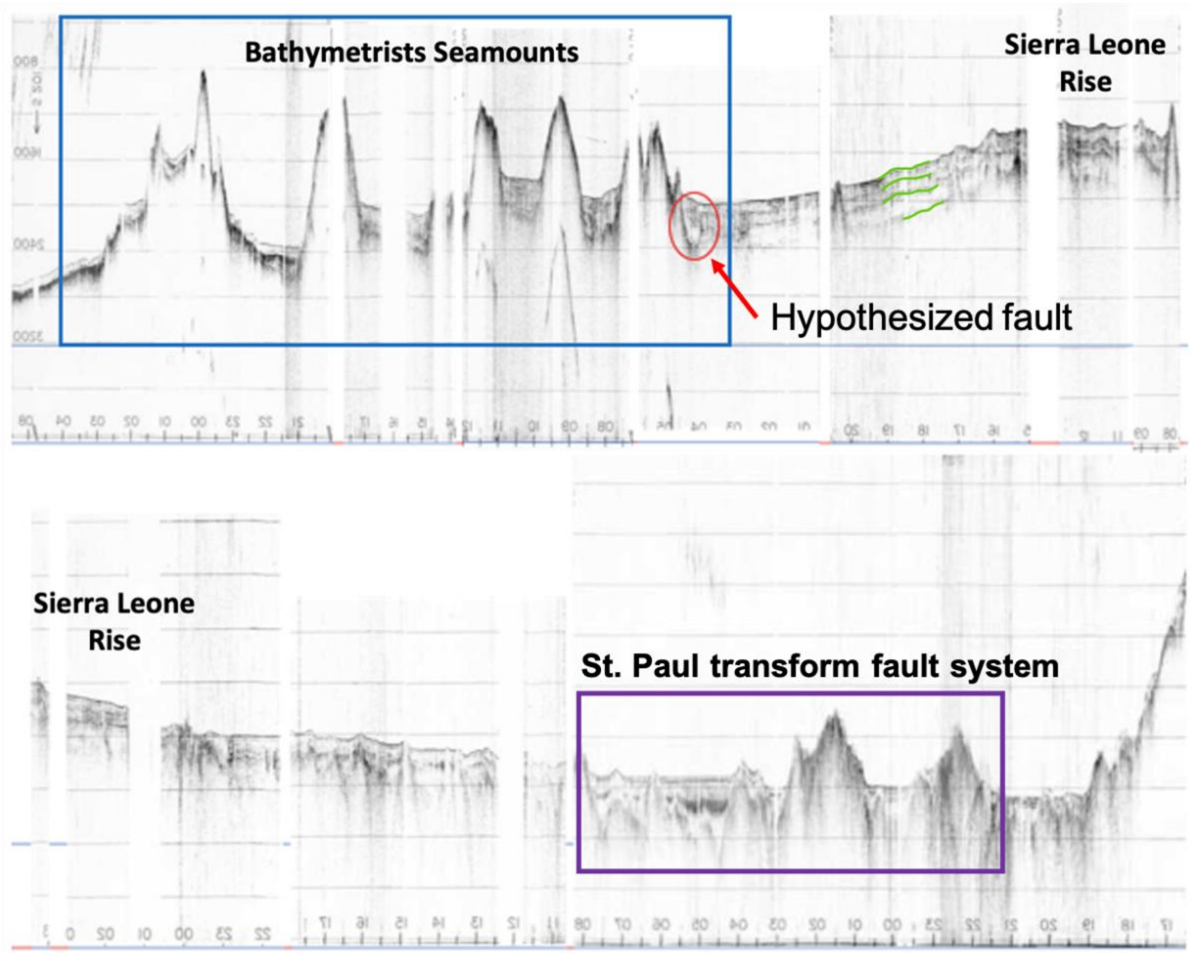

Figure 3-6. Seismic data from expedition V2206 (Ewing, 1966); lines 75 to 622 are merged in this cross-section. Each individual line was scaled to represent an actual distance in kilometers. The total length of the profile is 1160 km. Vertical interval markers are one second apart. The Bathymetrists Seamounts are outlined with a blue box, while the red circle marks the location of the possible fault between the BSM and SLR crustal blocks. The St. Paul transform fault system is shown within the purple box. The green outlines represent the distinct layers made by correlating to the DSDP image from Site 366 (**Figure 2-1b**).

4. Methodology

4.1. Isostatic Modeling

The method implemented for this model is called isostatic modeling (Lillie, 1999; **Figure 4-1**). The concept of isostasy is based on the inter-relationships of the elevation and depth to the crust/mantle boundary (i.e., the Moho). Isostatic modeling implies that the pressure exerted by various crustal blocks at a given depth remains the same for a system in isostatic equilibrium. This can be expressed by the following equation:

$$P = \rho g h, \qquad \textbf{[3]}$$

In this equation, P is the pressure exerted by the crustal block, ρ is the density of the crustal block, h is the block's thickness, and g is the acceleration due to gravity force. The gravity variable remains constant throughout the study area, so it can be dropped. In other words, the isostatic equilibrium can be expressed as:

$$\Sigma(\rho h)_{location\ 1} = \Sigma(\rho h)_{location\ 2} \qquad \textbf{[4]}$$

As the ages of the tectonic structures in the study are relatively old (ranging from 90 to ~40 Ma), isostatic equilibrium can be assumed throughout the models. For modeling, a compensation depth of 25 km was used, as there should be no crustal material beneath this depth, only the upper mantle. Balancing the pressures (**equations [3]** and **[4]**) to an isostatic equilibrium allows to determine the thickness for each of the crustal layers.

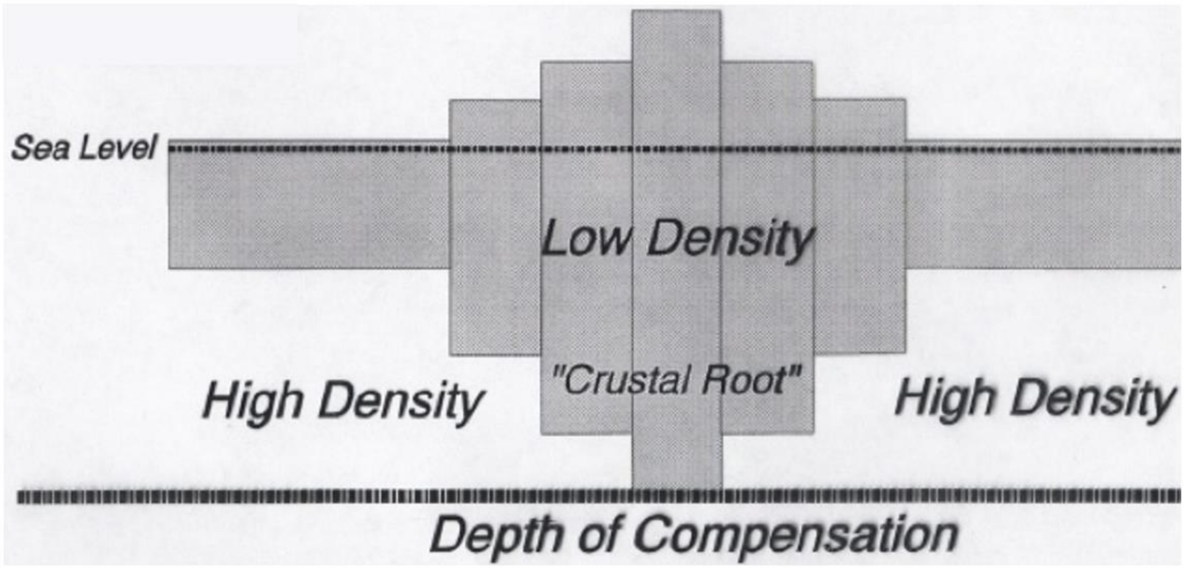

Figure 4-1. Airy Model shows an example of isostatic modeling, showing the relationship between different crustal segments and depth of compensation.
(Figure taken from Lillie, 1999)

4.1.1. Velocity to Density Conversion

From the Jones et al. (2015) research, sites with the thinner crust over the basin and mapped Moho served for calibration purposes (locations D, E, and F in **Figure 2-5 A**). The experiment determined seismic velocity ranges for each layer (**Figure 2-5 B**). The densities of the sedimentary cover derived from the seismic velocities using the Gardner equation (Gardner et al., 1974):

$$\rho = 0.31Vp^{0.25} \qquad \textbf{[5]}$$

where ρ is density, and Vp is the seismic velocity in meters/second.

This equation was used to convert the density of sediments in each model. However, some of the seismic velocities vary slightly between different locations, resulting in too many parameters. To reduce uncertainty, the density values for each modeled layer were averaged,

resulting in a single value. The densities for the rest of the model (water and upper mantle) were assumed based on the literature for given lithologies. As a result, the following parameters were used:

Sediment 2.3 g/cc

Extrusive upper crust 2.65 g/cc

Intrusive lower crust 2.85 g/cc

Magmatic underplating 3.0 g/cc

These values are within the expected range for the lithologies expected in the study area (Jones et al., 2015). Densities for water and the upper mantle did not have to be derived. The density of water is a known value, while the density of the upper mantle must be assumed as the standard value used in the literature (Lille, 1999):

Water 1.0 g/cc

Upper mantle 3.3 g/cc

Once the density values are determined, they can be substituted in the isostatic **equation [4]** along with thickness values to solve for the thickness-density product.

4.1.2. Geological Constraints

The thickness of the water over the Bathymetrists Seamounts was estimated from the bathymetry map (**Figure 3-1**). Two end models were constructed (BSM A and BSM B) due to the variations in bathymetry over the seamounts, ranging from 3.8 to 1.7 km below sea level. Therefore, two different estimates for bathymetry were used as the end parameters to study how the crustal structures are affected by these variations in water thickness.

Sediment thickness over the Bathymetrists Seamounts was determined using seismic data from Line V2206 (**Figure 3-6**). The two-way travel time within the sedimentary layer over the BSM crustal block varies slightly but on average was estimated as 0.5 seconds. Using an assumed velocity of 2 km/s for the sediments (within the range determined by Jones et al. (2015),

Figure 2-5 B), the thickness of the sedimentary layer was calculated as 0.5 km. This value was used for the isostatic model over the Bathymetrists Seamounts (BSM A and BSM B).

The modeling started over the locations with known depths to all layers (locations 1, D, E, and F in **Figure 2-5 A**) that serve as calibration models. As the thicknesses of all subsurface layers were constrained from refractions (**Figure 2-5 B**), the only parameters that could be varied during modeling were densities of subsurface layers. As the density-thickness products for these locations were calculated, they were compared. The agreement between the values in those locations serves as a validation of the computed densities (see results in **Chapter 5**).

Once the densities were confirmed, the models with unknown Moho depth were developed. For the Bathymetrists Seamounts, two models were constructed to acknowledge the slight variations in bathymetry across this block. As these were the end models, the most likely model for the BSM crustal block lies somewhere in between these two models.

4.2. Two-Dimensional Modeling

A two-dimensional model of the crustal structures beneath the Bathymetrists Seamounts and Sierra Leone Rise was built to further analyze their crustal architecture from gravity and magnetic data. The model was developed using the GM-SYS module of Geosoft software. This model integrates seismic reflection (**Figure 3-6**), gravity, and magnetic fields (**Figures 3-2** and **3-5**), in addition to bathymetry (**Figure 3-1**) and refraction data (**Figure 2-5**) used in the isostatic model.

To begin modeling, sea-bottom topography was extracted from the bathymetry map (**Figure 3-1**). Next, the seismic reflection image from expedition V2206 (**Figure 3-6**) was brought in as a background to trace the sedimentary layers accurately. As the seismic line’s vertical axis is in a two-way travel time, seismic velocities were assigned to each layer to convert to depths in kilometers.

Once the bathymetry and sediment layers were traced, the upper and lower crust, and magmatic underplating layers were added based on the guidance from refraction data (**Figure 2-5**) and the results of the isostatic modeling. Once all layers were included in the model, the physical properties, namely density and magnetic susceptibility, were assigned to each layer, so the expected gravity and magnetic anomalies could be computed.

Observed gravity and magnetic data were extracted from the Free-Air map (**Figure 3-2**) and magnetic anomaly (**Figure 3-5**) and imported into the model. They were then compared with the computed ones and the model was adjusted to ensure the fit in both potential fields. The resultant model should not only agree with the gravity and magnetic data, but also obey both seismic reflection and refraction constraints and remain geologically reasonable. The magnetic susceptibility values for crustal layers were chosen to better match the magnetic data; each subsurface layer had a different magnetic susceptibility based on the lithology.

The depths from Jones et al. (2015) were extracted and plotted on the model to guide the modeling and match with the observed gravity field. However, only location 1 intersected the seismic line V2206 and was taken into consideration to accurately match the adjusted layer thicknesses. The other locations (2, 3, and D), although close to the seismic line, were not as accurate in determining the depth for each layer, but were still used as an approximated guide/range to determine the thickness for the layers.

The magnetic field was matched based on the assigned magnetic polarities. In other words, the crustal ages were determined (**Figure 2-3**), and the magnetic polarities (normal or reversed) were determined to represent different magnetic chrons. Normal polarity was assigned a positive magnetic susceptibility value, while reversed polarity was assigned a negative value.

5. Results

5.1. Isostatic Modeling

The resulting models are shown in **Figure 5-1**. Each section is labeled SLR for Sierra Leone Rise, SLB for Sierra Leone Basin, and BSM for Bathymetrists Seamounts, as well as their depth to Moho. **Figure 5-1 A** demonstrated the balanced columns for all the modeled locations (see the map in **Figure 2-5 A**). The locations with unknown depth to Moho are SLR1, SLB D, and SLB E (outlined with the red boxes in **Figure 2-5 A**), through isostatic modeling a depth to Moho was determined. The cumulative density-thickness product (**equation [3]**) for all these locations resulted in around 68.05 [km·g/cc]. Then, the rest of the models were completed (**Figure 5-1 B**), the depth to the Moho was found by matching the density-product parameter to this same value of 68.05 [km·g/cc].

The result of the isostatic modeling over the BSM block (**Figure 5-1**) suggests that the crust is about 20 km thick in both BSM A and BSM B models and is composed of the extrusive upper crust (3.4 to 4.4 km) and intrusive lower crust (6.0 to 6.3 km) and includes 6.0 to 7.1 km of magmatic underplating. Models BSM A and BSM B were developed as end members for varying water depth that impacts the balancing of the other layers (see differences in layer thickness between BSM A and BSM B in **Figure 5-1 B**). These end models suggest that the magmatic underplating is necessary beneath the BSM crustal block and that the minimum thickness of that magmatic underplating is 6.0 km. If no magmatic underplating is included beneath the BSM segment, the estimated density-thickness product of 68.05 [km g/cc] would not be met, resulting in a huge unbalance in the isostatic model.

The thick crust of the Bathymetrists Seamounts determined from the isostatic modeling is consistent with the Bouguer Anomaly (**Figure 3-4**). The evident gravity lows over the Bathymetrists Seamounts and the Sierra Leone Rise suggest that the crustal structures of these blocks should be similar. As the magmatic underplating was determined for the Sierra Leone Rise from the refraction experiment (**Figure 2-5 B**), it was also included in the model of the BSM (**Figure 5-1 B**). Therefore, the conclusions of the isostatic modeling are supported by the gravity data.

The development of the isostatic model always presents some uncertainty related to possible errors in thicknesses of all layers and their densities. Models for the Sierra Leone Basin (SLB D and SLB E) were used as a control group because their boundaries were clearly defined by the refraction experiment of Jones et al. (2015). Modeling started with a control group (SLB models and SLR 1), then the other models from Jones et al. (2015) with unknown depth to Moho were mapped to complete the missing depth to Moho. Last, the BSM models were constructed as end parameters. The isostatic modeling and two-dimensional model revealed that the crustal architecture beneath the Sierra Leone Rise and the Bathymetrists Seamounts is in fact similar.

SLR 1	h	ρ	P = ρ x h
	3.00	1.00	3.00
	1.20	2.30	2.76
	3.10	2.65	8.22
	5.50	2.85	15.68
	6.20	3.00	18.60
	6.00	3.30	19.80
Total depth:	25.00	Total P:	**68.05**

SLR 2	h	ρ	P = ρ x h
	4.90	1.00	4.90
	0.50	2.30	1.15
	2.00	2.65	5.30
	3.00	2.85	8.55
	0.00	3.00	0.00
	14.60	3.30	48.18
Total depth:	25.00	Total P:	**68.08**

SLR 3	h	ρ	P = ρ x h
	4.00	1.00	4.00
	0.50	2.30	1.15
	1.90	2.65	5.04
	4.60	2.85	13.11
	4.80	3.00	14.40
	9.20	3.30	30.36
Total depth:	25.00	Total P:	**68.06**

SLR 4	h	ρ	P = ρ x h
	4.40	1.00	4.40
	0.70	2.30	1.61
	1.30	2.65	3.45
	6.20	2.85	17.67
	0.00	3.00	0.00
	12.40	3.30	40.92
Total depth:	25.00	Total P:	**68.05**

SLB D	h	ρ	P = ρ x h
	4.80	1.00	4.80
	0.40	2.30	0.92
	1.40	2.65	3.71
	4.70	2.85	13.40
	0.00	3.00	0.00
	13.70	3.30	45.21
Total depth:	25.00	Total P:	**68.04**

SLB E	h	ρ	P = ρ x h
	4.80	1.00	4.80
	1.20	2.30	2.76
	1.40	2.65	3.71
	2.90	2.85	8.27
	0.00	3.00	0.00
	14.70	3.30	48.51
Total depth:	25.00	Total P:	**68.05**

SLB F	h	ρ	P = ρ x h
	4.00	1.00	4.00
	2.60	2.30	5.98
	1.80	2.65	4.77
	3.30	2.85	9.41
	0.00	3.00	0.00
	13.30	3.30	43.89
Total depth:	25.00	Total P:	**68.05**

Lithology	ρ
water	1.00
sediment	2.30
extrusives	2.65
intrusives	2.85
magmatic underplating	3.00
upper mantle	3.30

BSM A	h	ρ	P = ρ x h
	2.80	1.00	2.80
	0.50	2.30	1.15
	4.40	2.65	11.66
	6.30	2.85	17.96
	6.00	3.00	18.00
	5.00	3.30	16.50
Total depth:	25.00	Total P:	68.07

BSM B	h	ρ	P = ρ x h
	3.00	1.00	3.00
	0.50	2.30	1.15
	3.40	2.65	9.01
	6.00	2.85	17.10
	7.10	3.00	21.30
	5.00	3.30	16.50
Total depth:	25.00	Total P:	68.06

Figure 5-1. A) The densities and thicknesses of each individual column used for the isostatic modeling; see locations in **Figure 2-5 A**. Sections with red box were those without a pre-determined Moho (SLR 2, 3, and 4, as well as BSM A and B). The thickness was determined from the refraction experiment (**Figure 2 B**). Each lithology is color coded. The resultant density-thickness product (**Equation 2**) for each column is highlighted in yellow.

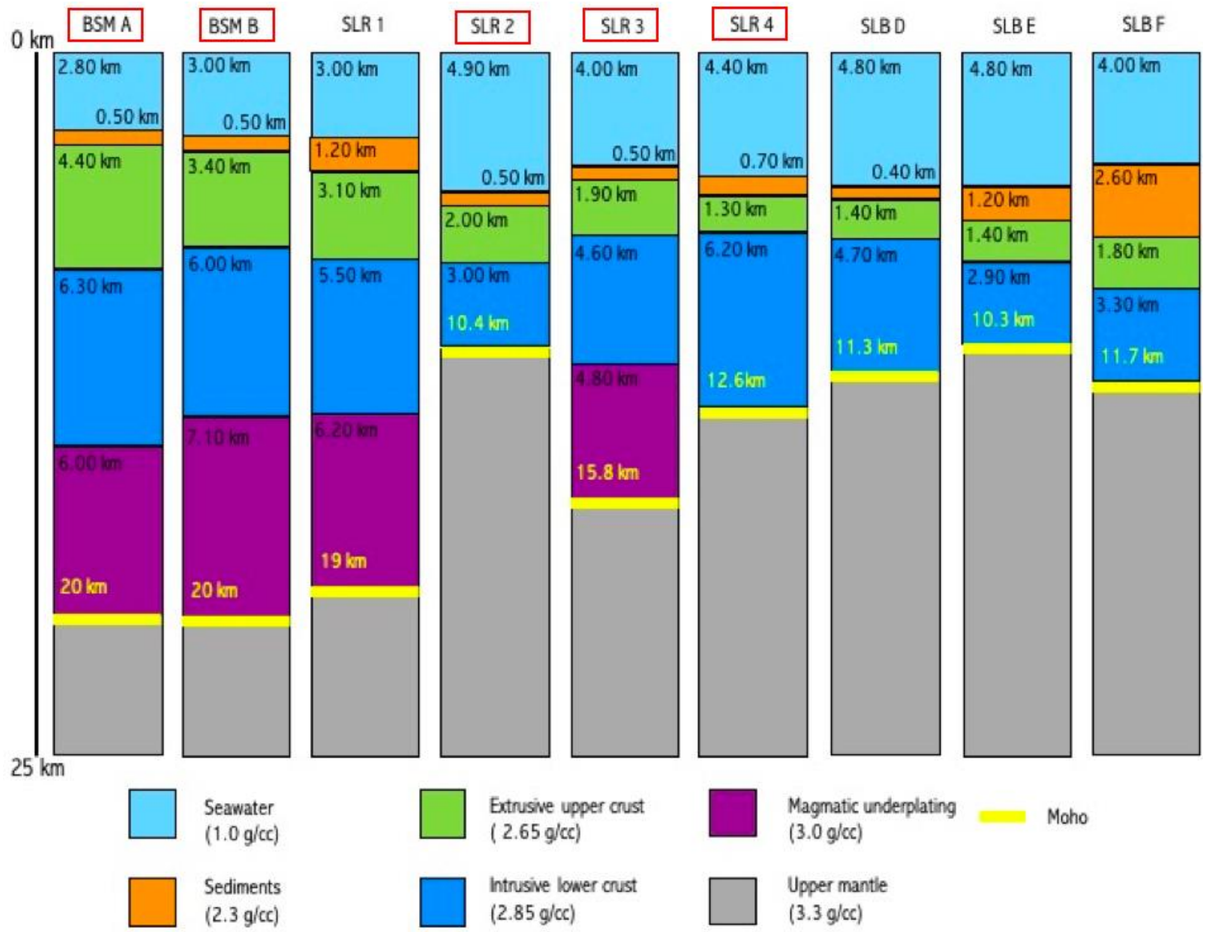

Figure 5-1. B) The resultant columns for each modeled location. The Moho depth was determined at locations with previously unknown Moho depth: BSM A, BSM B, SLR 2, 3, and 4 (outlined in red). The rest of the models were used for calibration.

5.2 Two-Dimensional Model

The resulting two-dimensional model can be seen in **Figure 5-2 A**. The computed gravity field (thin black line) fits accordingly to the extracted gravity data (black dotted line). The model uses the same layers as the isostatic model, water, sediment, extrusive upper and intrusive lower crust, and magmatic underplating (**Figure 5-1**), along with the same densities were used for each layer to ensure geologic consistency between the two models. Additionally, the thickness for each layer is constrained by seismic reflection (**Figure 3-6**), for the water and sediment layers, as well as the refraction data (red crosses, which depths come from the Jones et al. (2015) study;

Figure 2-5). Moreover, different consideration was given to refraction constraints based on the locations (1, 2, 3, D) proximity to the model line (expedition V2206 path; **Figure 3-6**). Overall, this model agrees with the isostatic model findings and is consistent with the refraction data from Jones et al. (2015).

Unlike the isostatic model, the 2-D model offers a more continuous view of the possible crustal architecture beneath the study area. The normal oceanic crust is seen to be interrupted by both the Bathymetrists Seamounts and Sierra Leone crust. Magmatic underplating is required beneath the Bathymetrists Seamounts to agree with gravity data, as well as the Sierra Leone Rise which was known. Once again, if no magmatic underplating is included beneath the BSM, the calculated gravity does not match the observed, creating an outstanding difference of almost 70 mGal (**Figure 5-2 B**).

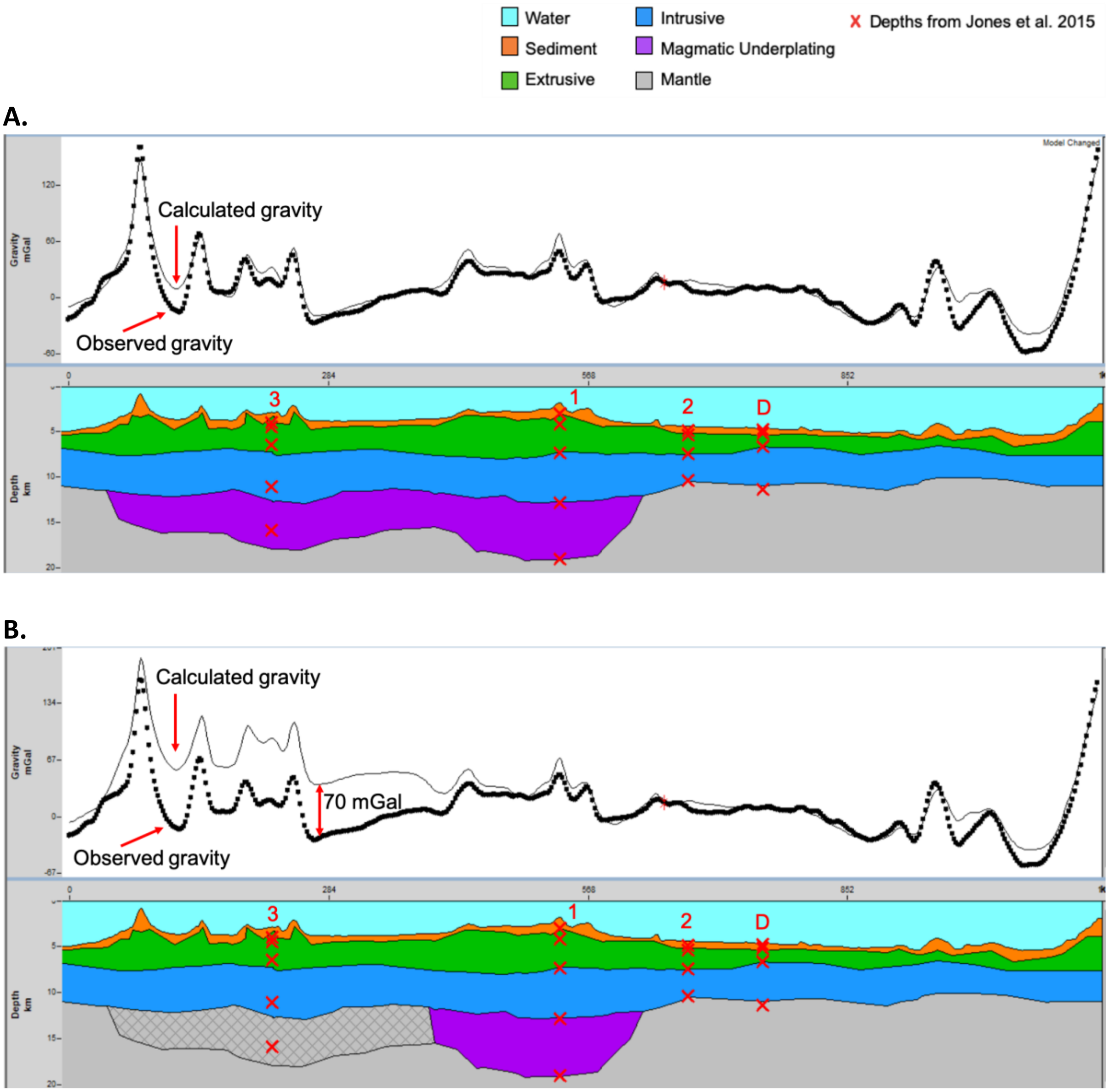

Figure 5-2. A) The resultant model over seismic line V2206. Bathymetry, sediment, extrusive, intrusive, and magmatic underplating layers were adjusted to fit the extracted gravity data. Depths from Jones et al. (2015) columns 3, 1, 2, and D are displayed as red crosses respectively. **B)** Same model without magmatic underplating beneath the BSM, showing a 70 mGal difference between observed and calculated gravity.

This result confirms what was deduced from the isostatic model, the BSM requires magmatic underplating beneath. This concludes, once again, both the Sierra Leone Rise and Bathymetrists Seamounts have very similar crustal architectures. However, although the Bouguer anomaly map (**Figure 3-4**) shows a slight low between the Sierra Leone Rise and the Bathymetrists Seamounts, it is not as prominent as the BSM and SLR crust areas. The extending magmatic underplating connecting the two separate areas is noticeably thinner than directly below the BSM and SLR crustal blocks.

The same model (**Figure 5-2 A**) was used to match observed magnetic data (**Figure 5-3**). Using different magnetic polarities by assigning positive magnetic susceptibility (solid color) for the crust that originated during a normal polarity, and negative magnetic susceptibility (diagonal lines) for the crust that originated during reversed polarity, calculated magnetic data was matched to the observed magnetic anomalies. The model beneath the Sierra Leone Basin matches well with known polarity reversals. Using the crustal ages from **Figure 2-3 B** and the known reversals from Walker et al. (2018) between 59 and 64 Ma, a good match between observed and computed magnetic anomalies over the Sierra Leone Basin was achieved (**Figure 5-3**). Furthermore, different polarities are recorded in the crust beneath the SLR, however, some modifications in physical properties may be required to better match the calculated with the observed magnetic data over the SLR crustal block. Now, the observed magnetic data over the BSM displays several changes in polarity. The BSM is supposed to be within the crustal age of the Cretaceous Magnetic Quiet Zone, meaning no changes in the direction of the magnetic field should occur and the model should display normal polarity anomalies (solid color of the modeled blocks). However, the BSM clearly requires the crust to have magnetic susceptibilities of both normal and reversed polarities to match the observed magnetic data.

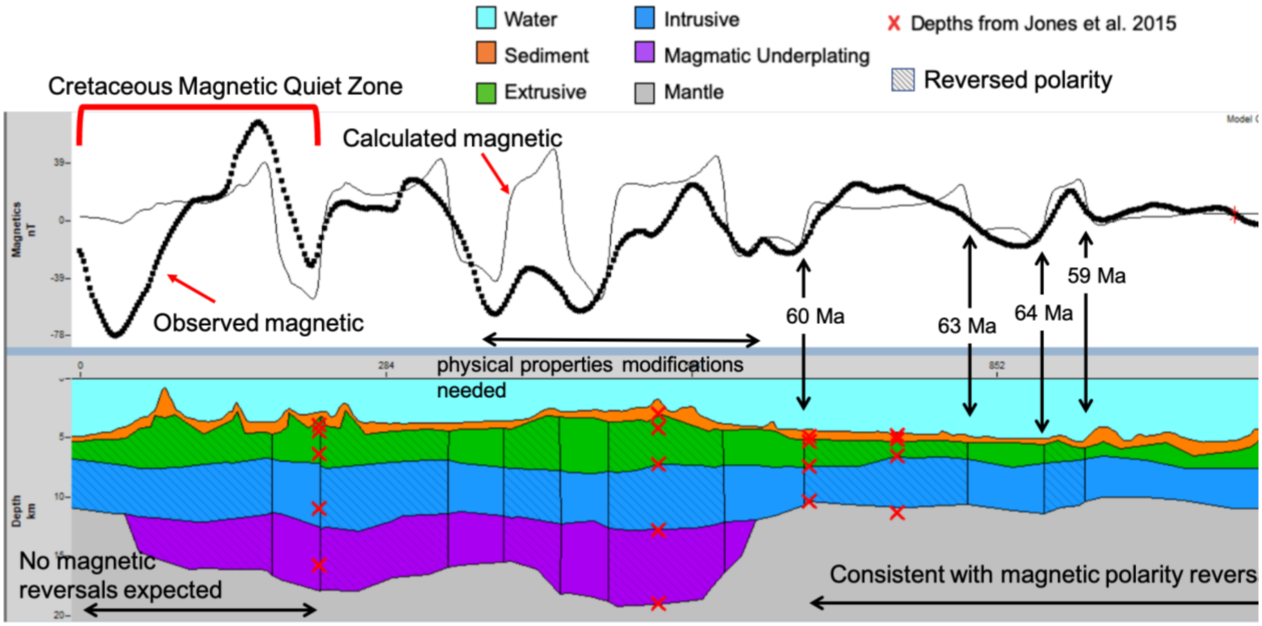

Figure 5-3. The resultant magnetic model over seismic line V2206. To the right, the Sierra Leone Basin is consistent with polarity reversals, while the Sierra Leone Rise segment still needs modifications to physical properties of the layers. The BSM segment contradicts the Cretaceous Magnetic Quiet Zone, as the observed magnetic data clearly requires changes in polarity throughout.

6. Discussion

The development of both isostatic (**Figure 5-1**) and 2D integrated (**Figure 5-2**) models proves that the crust beneath the Bathymetrists Seamounts resembles that of the Sierra Leone Rise. The SSC hypothesis (**Figure 2-4**) requires for the crust beneath the Bathymetrists Seamounts to be thinner than the one of the Sierra Leone Rise. However, both the isostatic model and the two-dimensional model show that the Bathymetrists Seamounts and Sierra Leone Rise share very similar crustal architecture, challenging the SSC hypothesis for the BSM formation (Schade, 2018; Hübscher et al., 2019).

This result triggered a new hypothesis: The Sierra Leone Rise and Bathymetrists Seamounts crustal blocks (not the seamounts, the original crust only) may have originated at the same time over the same source, resulting in similar crustal architecture involving magmatic underplating. If this is the case, the BSM crustal block appears to be displaced at least 100 km by a hypothesized left-lateral fault striking northeast to southwest between these blocks (**Figure 6-1**). The strike of this hypothesized fault is like the overall trend of the seamounts. This suggests these structures are related and were potentially formed at the same time, well after the thickened crust of the BSM was formed.

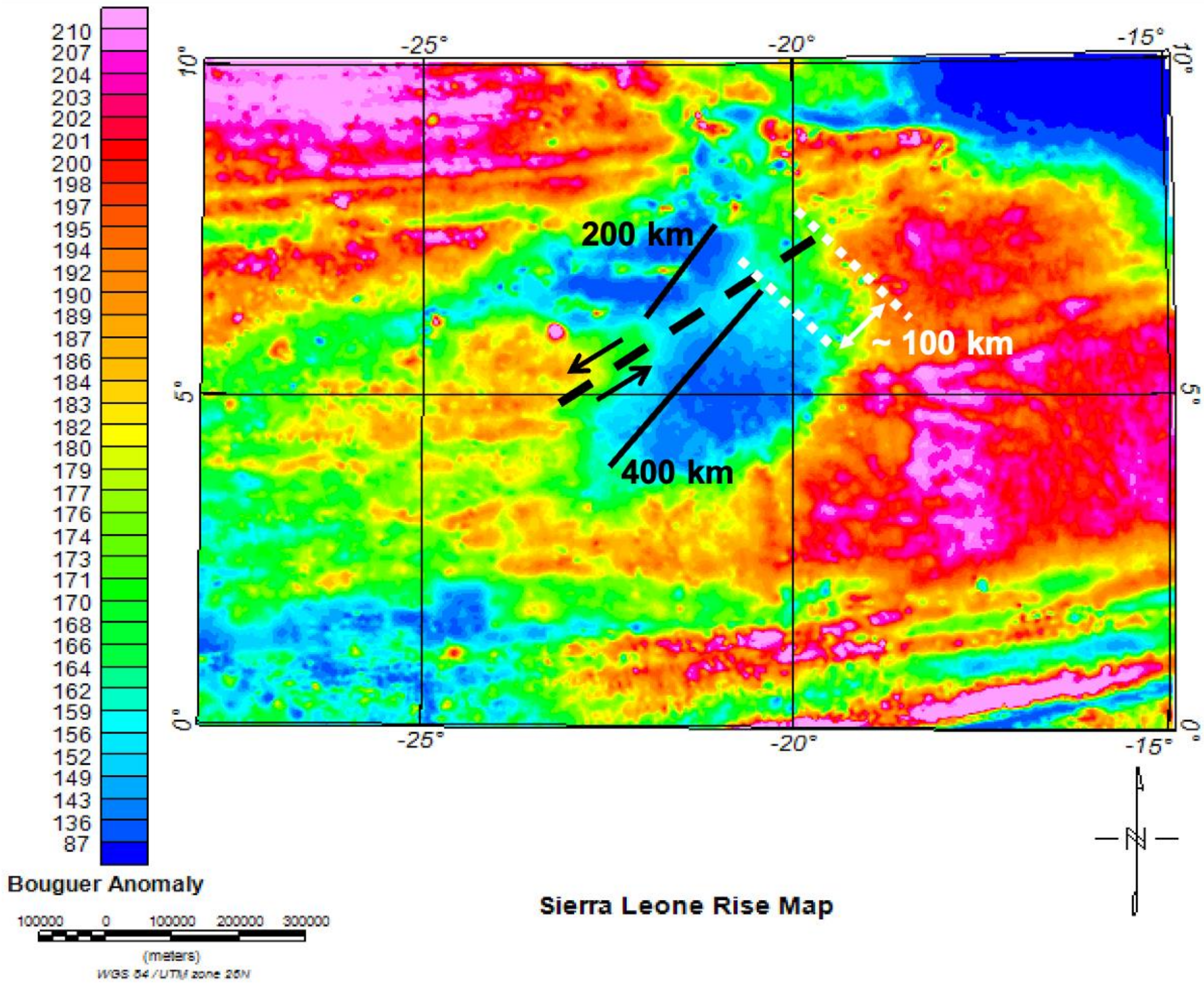

Figure 6-1. Location of hypothetical fault offsetting both the Sierra Leone and Bathymetrists Seamounts blocks. The offset is estimated to be at least 100 km.

The presence of this hypothesized fault explains the observed difference in the total lengths of the Cearà and the Sierra Leone Rise. As they originated around the same time, the Cearà Rise and Sierra Leone Rise should have the same dimensions. However, the Cearà is noticeably longer (**Figure 1-1**). If the Bathymetrists Seamounts block is restored using the hypothesized left-lateral transform fault (**Figure 6-1**), the total length of the SLR (combined with the BSM) would match the one of the Cearà Rise (600 km). Furthermore, the seamounts would have originated well after the crust they reside on, which is consistent with the dredging results (Peyve and Skolotnev, 2009; Skolotnev et al., 2017) and agrees with the magnetic analysis (**Figure 5-3**).

This fault can be observed in the vintage seismic reflection cross-section through the study area (marked with the red circle in **Figure 3-6**). This feature in the red circle is believed to be a transform fault as it presents similar characteristics on the seismic reflection as the northern part of the St. Paul transform fault system. To test this hypothesis, recent geophysical data provided by Hübscher et al. (2019), including seismic recorded simultaneously with marine gravity and magnetic fields, will be analyzed. The analysis of these data will help to develop more 2-D models through different locations over the BSM to study variations in crustal features that can potentially give more information on the tectonic history of the seamounts.

7. Conclusions

The integrated analysis of geophysical data over BSM and SLR in the central Atlantic led to the following conclusions:

(1) The crust beneath the Bathymetrists Seamounts is ~ 20 km thick and includes at least 6 km of magmatic underplating.

(2) The crustal architecture of the Bathymetrists Seamounts crustal block (derived from isostatic modeling and further supported by the two-dimensional model) and that of the Sierra Leone Rise block (determined from the refraction experiment and further supported by a two-dimensional model) appear to be similar. This conclusion is consistent with the Bouguer gravity anomaly (**Figure 3-4**) showing the pronounced gravity lows over both crustal blocks corresponding to the thick crust.

(3) The similarity in the crustal architecture of the Bathymetrists Seamounts and Sierra Leone Rise blocks trigger the hypothesis about these blocks being formed at the same time over the same source. In this case, the two crustal blocks were possibly offset more than 100 km by a hypothetical left-lateral transform fault (**Figure 6-1**). The presence of this fault is supported by several observations: 1) The total length of the Cearà Rise crustal block (600 km) is longer than the one of the conjugate Sierra Leone Rise (400 km). If the Bathymetrists Seamounts crustal block is considered when measuring the length of the Sierra Leone Rise the total length will match (about 600 km). 2) The strike of the hypothesized fault is similar to the trend of the Bathymetrists Seamounts, suggesting that the fault was active at the time the seamounts formed. 3) The characteristic fault signature is observed in the vintage reflection cross-section (**Figure 3-6**). 4) The seamounts are younger than the crust they reside on which is consistent with dredging and magnetic data.

To test this new hypothesis, more analysis of seismic and potential fields over the Bathymetrists Seamounts and Sierra Leone Rise is required. This will be done with recent geophysical data from Hübscher et al. (2019).

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