DETERMINATION OF MOHO DEPTH BENEATH THE OKAVANGO AND KAFUE RIFT USING SPECTRAL ANALYSIS WITH PIECEWISE REGRESSION (SAPR) OF SATELLITE GRAVITY DATA

By
Farjana Monsur Mily
Bachelor of Science in Geology
University of Dhaka
Bangladesh
2015

Master of Science in Geophysics
University of Dhaka
Bangladesh
2017

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Thesis Approved:

Dr. Mohamed Abdelsalam

Thesis Adviser

Dr. Daniel A. Laó Dávila

Dr. Jack Pashin

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Name: Farjana Monsur Mily
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Abstract:
The research investigated the use of satellite gravity data to map the lithospheric structure under the Okavango Rift Zone (ORZ) in northwest Botswana and the Kafue Rift Zone (KRZ) in Zambia. The tectonic extent and subsurface lithospheric structures are well understood for the ORZ in Botswana; however, very limited study has been found on the KRZ in Zambia, and lithospheric control is not well determined. This study primarily focused on the relationship between these rift systems to image the details of the Moho topography and the Precambrian crystalline basement. Spectral Analysis with Piecewise Regression (SAPR) of the World Gravity Model 2012 (WGM 2012) were used to determine the Moho depth and the Precambrian crystalline basement underneath the Okavango and Kafue rift. According to the Moho depth projections of the SAPR analysis, the thickness of the crust in the Kafue rift zone fluctuates between 26 km to 36 km, while the depth of the crust in the Okavango rift zone fluctuates between 20 km to 32 km. The depth of the mid-crustal discontinuity was determined between 10 km to 14 km for the Okavango and Kafue rift zone, which could be the depiction of Conrad discontinuity. Three 2D forward gravity models were created to contrast them with the outcomes of the spectral analysis of 2D gravity data. The 2D forward gravity model results suggest crustal thinning and a shallower Moho layer beneath the Okavango and Kafue rift zone. Determining the depth of Moho within this region will connect the gap in scientific knowledge of subsurface lithospheric control between the Okavango and Kafue rift zone. The objective of this investigation is to extend the knowledge of the Kafue rift system, which has been recently studied, by integrating it with the more established branches of the East African Rift System. This will aid in the creation of a comprehensive framework for the entire system.

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CHAPTER I

INTRODUCTION

According to Macgregor (2015), The East African Rift System (EARS) represents the most notable example of a presently active rift system. The East African Rift System (EARS) displays different types of tectonic behaviors, lateral faulting, noticeable topographic differences, the impact of earlier geological formations, and volcanic activities related to the rift (Braile et al., 2006). The EARS is categorized into three branches: eastern, western, and southwestern (Figure 1.1a). Saria et al. (2014) and Stamps et al. (2008) state that the eastern and western branches of the EARS experience an extension of approximately 5-6 mm/year due to the separation of plates at the Nubian-Somalian plate boundary. However, this extension rate gradually declines towards the southwestern branches, where it is approximately 1 mm/year across the EARS.

Modisi et al. (2000) assert that the Okavango Rift Zone (ORZ) is viewed as the dynamic extensional tectonic system that symbolizes the EARS' southwestern region (Figure 1.1b). This southwestern part expands with a width of ~250 km for ~1700 km southwestward of Malawi and Tanganyika Rift (Mosley-Bufford et al., 2012). According to Kinabo et al. (2008) and Huntsman-Mapila et al. (2006), the rift system, which is approximately 200,000 years old, is the most recent rift basin in the EARS' southwestern branch. It is deemed less developed than the eastern and western branches of EARS. During the onset of EARS, a set of extensional structures with ENE and

NNW orientations were revived within the Kafue Rift Zone (KRZ), a segment of the southwestern branch with a late Paleozoic-early Mesozoic age (Evans et al., 2019; Unrug, 1987). This rift segment generally aligns with Botswana's NE-SW strike of the Okavango rift zone. However, there is insufficient knowledge about how the ORZ connects with the KRZ or other parts of the EARS (Evans et al., 2019).

Different geophysical methods such as aeromagnetic, gravity, shallow magnetotelluric (MT), and remote sensing were extensively used to comprehend the development, kinematics, extent, and crustal thickness within the EARS (Evans et al., 2019, Katumwehe et al., 2015 Leseane et al., 2015, Kinabo et al., 2008-2007). 2D radially averaged power spectral analysis from gravity data has been widespread since the 1960s (Spector and Bhattacharyya, 1966) and popularized by Spector and Grant (1970). Though spectral analysis was applied since the 1960s, since the 1990s, it has been used increasingly due to new computed-based interpretation tactics (Mickus and Hussein, 2015). In recent times, the 2D power density spectrum analysis of aeromagnetic and gravity data has been extensively employed in the ORZ of the Botswana region to estimate the thermal structure and thickness of the crust by utilizing the 3D inversion technique (Leseane et al., 2015; Kinabo et al., 2007). Although significant work was accomplished in ORZ of Botswana, KRZ of Zambia is entirely new to study. The structure of the lithosphere below Zambia endures poorly defined (Evans et al., 2019). Significant studies have already contributed to the southwestern branch, such as the Botswana area, but a correlation between Zambia and the Botswana Rift system is missing.

This study uses satellite data of gravity method to address the connection between the Okavango Rift from Botswana and Kafue Rift from Zambia and its lithospheric control. The objective of the study is to image the details of the topography of the Moho, Mid Crustal Discontinuity, and the Precambrian crystalline basement under the rift system. The motivation for pursuing this work is that the Kafue Rift System is fairly new and less studied than other rift systems surrounding the study area. Determining the depth of Moho within this area will bridge the understanding of subsurface lithospheric control between the Okavango and Kafue rift zone. It will contribute to the overall knowledge of the evolution of the southwestern branch of the EARS.

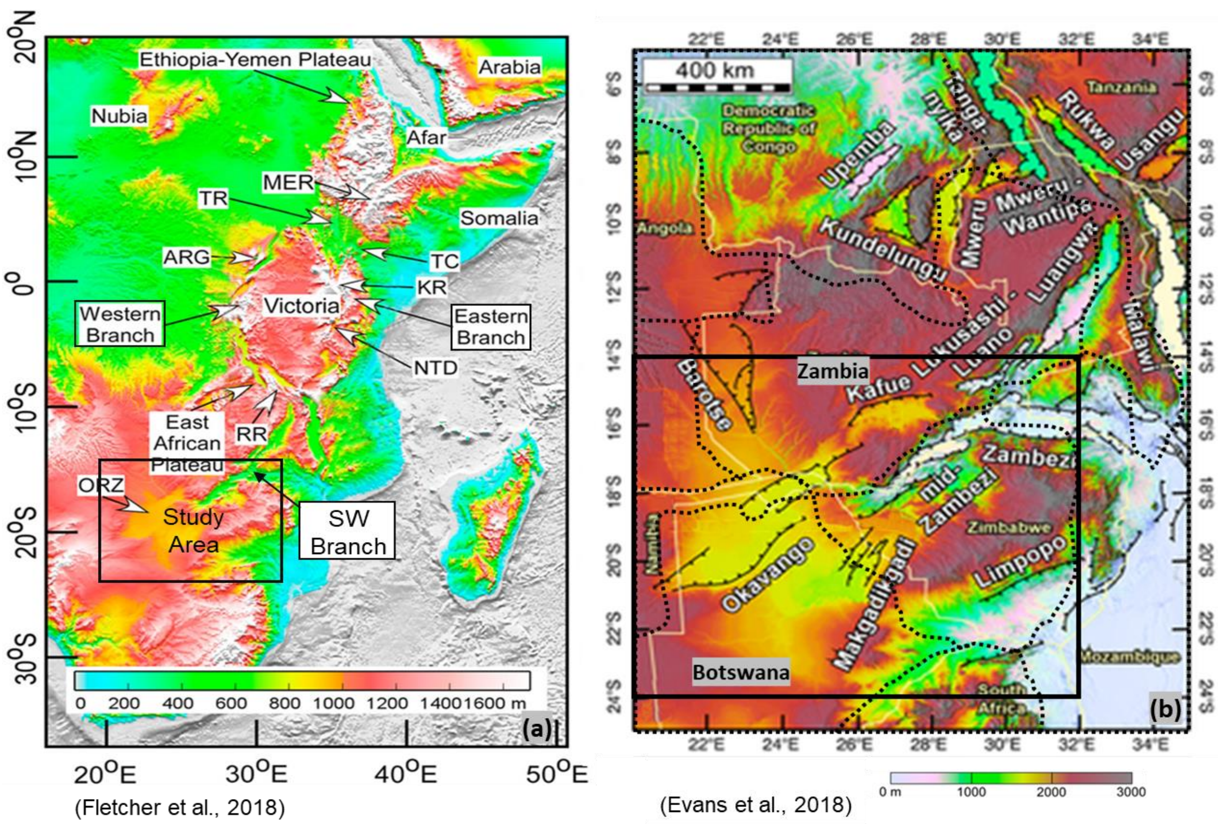

Figure 1.1: (a) Digital Elevation Map showing different branches of the EARS (Fletcher et al., 2018). (b) Shuttle Radar Topography Mission (SRTM) map exhibiting the study area located in the EARS and its major rift basins (Evans et al., 2019).

In this study, we use Spectral Analysis with Piecewise Regression (SAPR) of the World Gravity Model 2012 (WGM 2012) to determine the Moho depth and the Precambrian crystalline basement underneath the Okavango and Kafue rift. In addition, we compare the result with 2D gravity forward modeling from the same data, which implies an important role in Lithospheric structure during the ORZ and KRZ origination. This knowledge will assist us in creating the connection between these two rifts from Botswana and Zambia and understanding the possible crustal evolution, its tectonic implications, and the relationship between them while advancing the use of a new approach in imaging the Moho using spaceborne gravity data.

CHAPTER II

TECTONIC AND GEOLOGIC SETTING

The southwest branch of the EARS is extended to its southwestern end by the Okavango rift, situated in northwest Botswana. This rift zone is between Kalahari Craton and Congo Craton situated southeast and northwest, respectively. The ORZ developed within the northeast-trending Damara Mountain belt in the northwest and Ghanzi-Chobe Mountain belt in the southeast. (Leseane et al., 2015; Kinabo et al., 2008). A series of NE-SW oriented faults form the Makgadikgadi-Okavango-Zambezi (MOZ) basin, which includes a noticeable structural depression in which the Okavango rift zone was developed. (Figure 2.1b). These faults within the ORZ are normal, forming numerous graben structures within the underlying Precambrian basement rock (Modisi et al., 2000). Displacement occurred due to the tectonic action along these fault direction and caused in an uplift of the Zimbabwe-Kalahari axis (Ringrose et al., 2005). The geomorphology and the modern drainage pattern are largely influenced by the neotectonic activity within the ORZ, leading to the development of the largest intra-continental alluvium fans in Africa (Okavango Alluvial Fan).

The geology and Precambrian basement rock of the African continent is divided by few major cratonic areas bordered by trans-orogenic belts (Emishaw and Abdelsalam, 2023). The southern part of the Africa was mainly consisted of Congo craton (Congo – Bangweulu - Tanzania) at the center and the Kalahari craton (Kaapvaal – Zimbabwe – Niassa) at the southern part of the continent (Figure 2.1a). These two major cratons were divided by Trans-Southern Africa Orogeny which includes a series of NE-SW trending mountain belts (Damara – Ghanzi Chobe – Mwembeshi Shear Zone – Magondi). The Okavango and Kafue rift zone in southwestern part of the EARS extends towards this Trans-Southern African Orogenic belt.

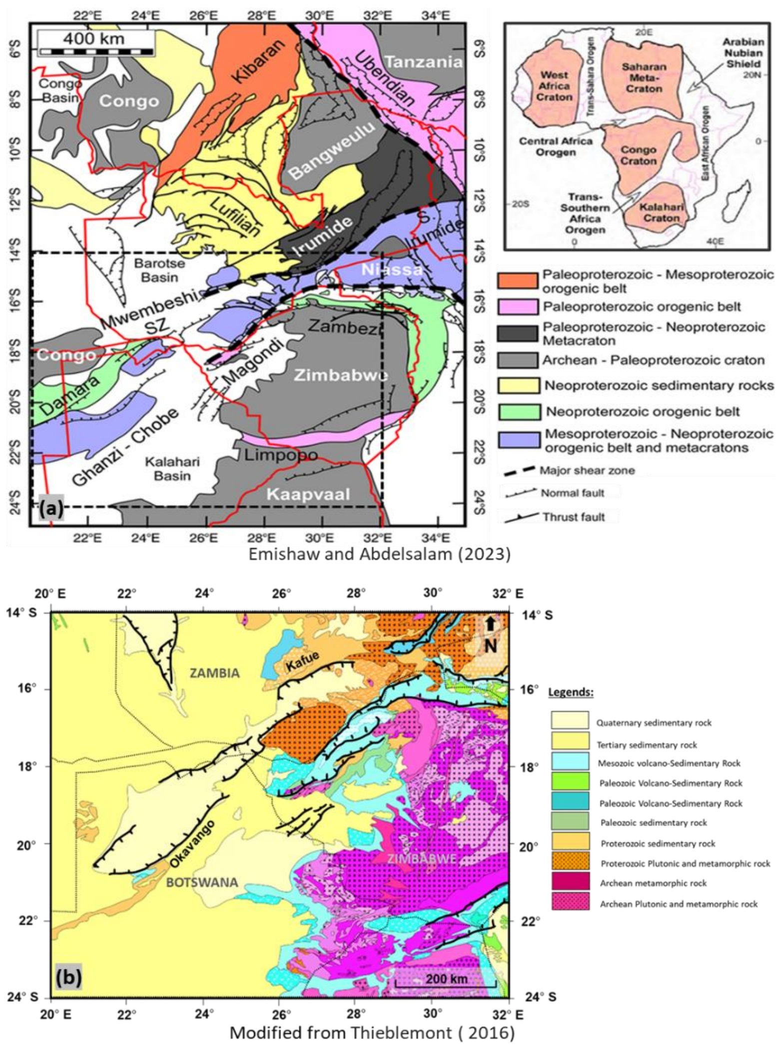

Figure 2.1: (a) The Precambrian basement rock map of the Okavango and Kafue rift zone showing major cratonic areas and orogenic belts (Emishaw and Abdelsalam, 2023). (b) Geologic map showing the sediment fills of the study area (Modified from Thieblemont, 2016).

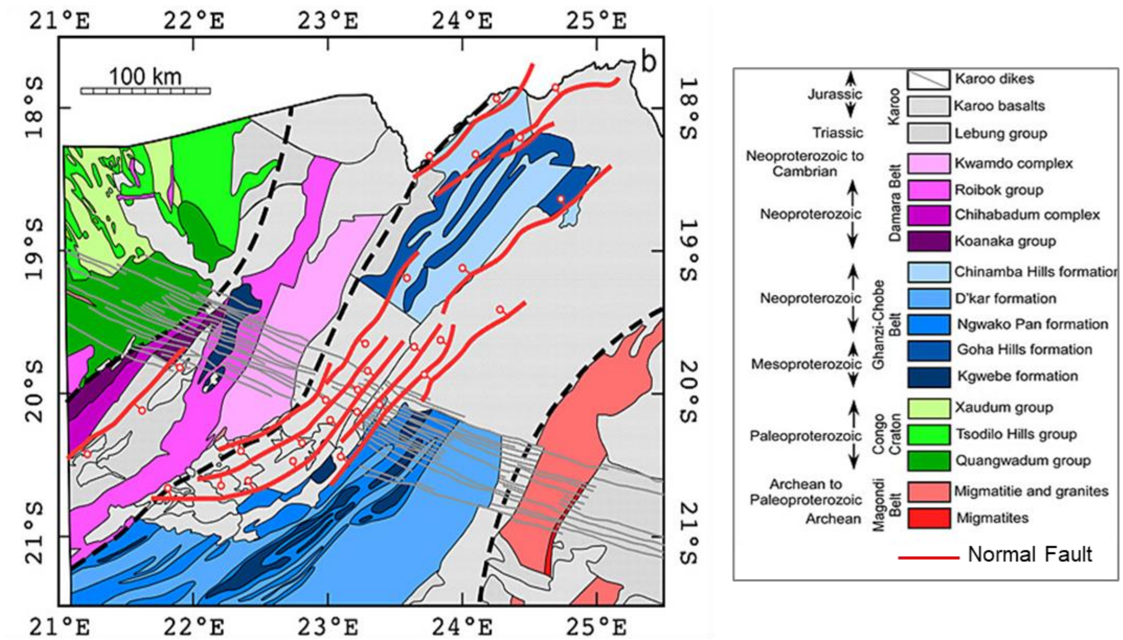

Figure 2.2: Geological map showing surface and subsurface Precambrian-Paleozoic geology of the ORZ. (Modified from Key and Ayres, 2000).

The northeast Okavango rift zone is underlain by volcanic rock and Karoo sedimentary rock, which rests unconformably on the Precambrian basement rock beneath the rift system (Figure 2.2). The volcanic rock represents the Jurassic age Karoo basalt, whereas the Triassic age Karoo sedimentary rocks mainly consist of sandstone and siltstone. The average thickness of the Karoo basalt within this rift system is nearly 1000 m, whereas the thickness of Karoo sedimentary rock is a maximum of 2000 m or unknown (Key and Ayres, 2000). On the other side of the Okavango Rift Zone, the PCB rock is covered by Kalahari alluvium and paleo lakes lacustrine sediments from Holocene time (Ringrose et al., 2005).

The exact age of rift initiation in Okavango Rift Zone is yet to be determined. However, different types of paleo-environmental reconstruction obtained from surface expressions like drainage pattern diversion, dunes, and basin sediments indicate the initiation of the rifting was during Holocene. According to Le Gall et al. (2002), rifting was set up after the 179 Ma Karoo dike intrusion dislodged along NE trending faults in ORZ. However, the main rifting phase occurred during the Neoproterozoic time, while the rifting commenced during the Mesoproterozoic. The Kalahari Suture Zone represents the present-day SE margin of the rift.

On the contrary, the Kafue rift represents the northeast-southwest strike of ORZ in Botswana. However, the structural development and tectonic advancement of the Kafue rift within the southwestern branch of EARS is yet to be constrained. The mid-Zambezi graben and the east-northeast trending Kafue are merged towards the east side of the Barotse basin (Unrug, 1987). The Kafue graben was developed due to the influence of the Mwembeshi and Zambezi dislocation zones which occurred by the impact relating the major Kalahari craton and Congo craton in the course of Neoproterozoic Pan-African Mountain building (Unrug, 1987). Although the extension rate is unknown for the Kafue rift system, the high heat flow within the Precambrian setting beneath Zambia studied by Chapman and Pollack (1975 and 1977) indicates the emergence of rifting events extends well into Zambia.

CHAPTER III

DATA AND METHOD

World Gravity Bouguer anomaly data were used to determine the depth of the Moho and the PCB over an area with an extent from 14°S – 24°S latitude and 20°E – 32°E longitude at the southwestern branch of the East African Rift System. The Geological Survey of Botswana acquired the data. The International Gravity Bureau provided the 2012 World Gravity Model (WGM) for this study. Using the Earth Spherical Model, a spatial resolution of approximately 9km was employed to generate the model (Balmino et al.,2012 and Bonvalot et al.,2012).

The Moho depth, Mid Crustal Discontinuity, and the PCB underneath the Okavango and Kafue rift were depicted using a two-dimensional radially averaged power spectral analysis of gravity anomalies. This technique has been extensively utilized for determining the depth of Moho, MCD, and PCB (Goussi Ngalamo et al., 2017; Leseane et al., 2015; Hussein et al., 2013; Maden, 2010; Stein and Cochran, 1985; Fairhead and Girdler, 1972). To reduce the influence of shallow sources, the WGM 2012 gravity anomalies were upscaled. This produced a residual gravity anomaly later separated into 437 sub-regions with 1° X 1° spatial resolution (approximately 110 km x 110 km) having 50% overlap (~55 km) in all directions. Therefore, substantial deviations in the Moho and PCB depth shorter than ~55 km distance were regarded as unlikely anomalies (Figure 3.1). A representative 2D radially averaged spectral curve was generated for each of the block from Bouguer gravity anomalies by plotting ln (Power Spectrum) and the wavenumber (k).

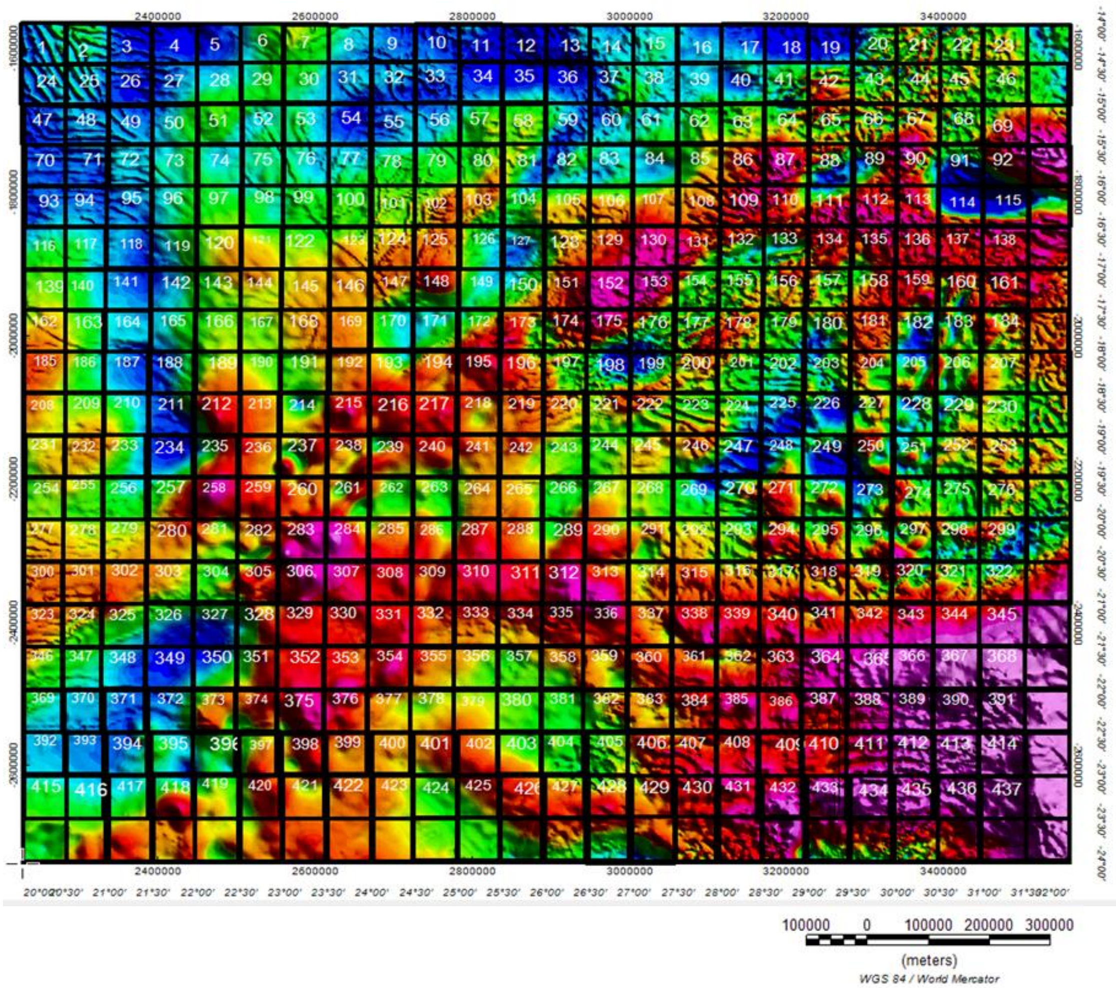

Figure 3.1 : Bouguer Gravity Anomaly map of the study area showing 437 blocks with 1° X 1° aerial coverage (~110 km x ~110 km).

2D Fourier integral is employed to convert the Bouguer gravity data into wavenumber domain from space domain, and 2D power spectrum data has been outlined in a Ln-P/wavenumber log map (Ngalamo et al., 2018) (Figure 3.2). Different density discontinuities can be represented by the depth of different gravity anomalies related to the linear parts within the spectral curve (Gomez-Ortiz et al., 2005 and Tselentis et al., 1988). Lithosphere-Asthenosphere Boundary (LAB), the deepest density boundary, corresponds to the steeper part of the curve with low frequency and low wavenumber (usually 0.0 – 0.05). On the contrary, the shallowest density boundary is known as PCB, characterized by a gentle slope in the spectrum curve with high frequency and much higher wavenumber (usually 0.25- 0.55). The segment of the spectral curve intermediate between these two boundaries corresponds to the Moho interface with intermediate wavenumber ranges from 0.05 to 0.25 (Sanchez-Rojas and Palma, 2014). In some cases, the upper area of the medium segment within the spectrum curve relates with the low frequency, low wavenumber with moderate slope, indicating another density interface named Mid Lithospheric Discontinuity (MLD). However, differentiating between Moho and MLD is often difficult, and that specified portion of the curve can be understood as a representation of the overall variation in density contrast across both the Moho and MLD.

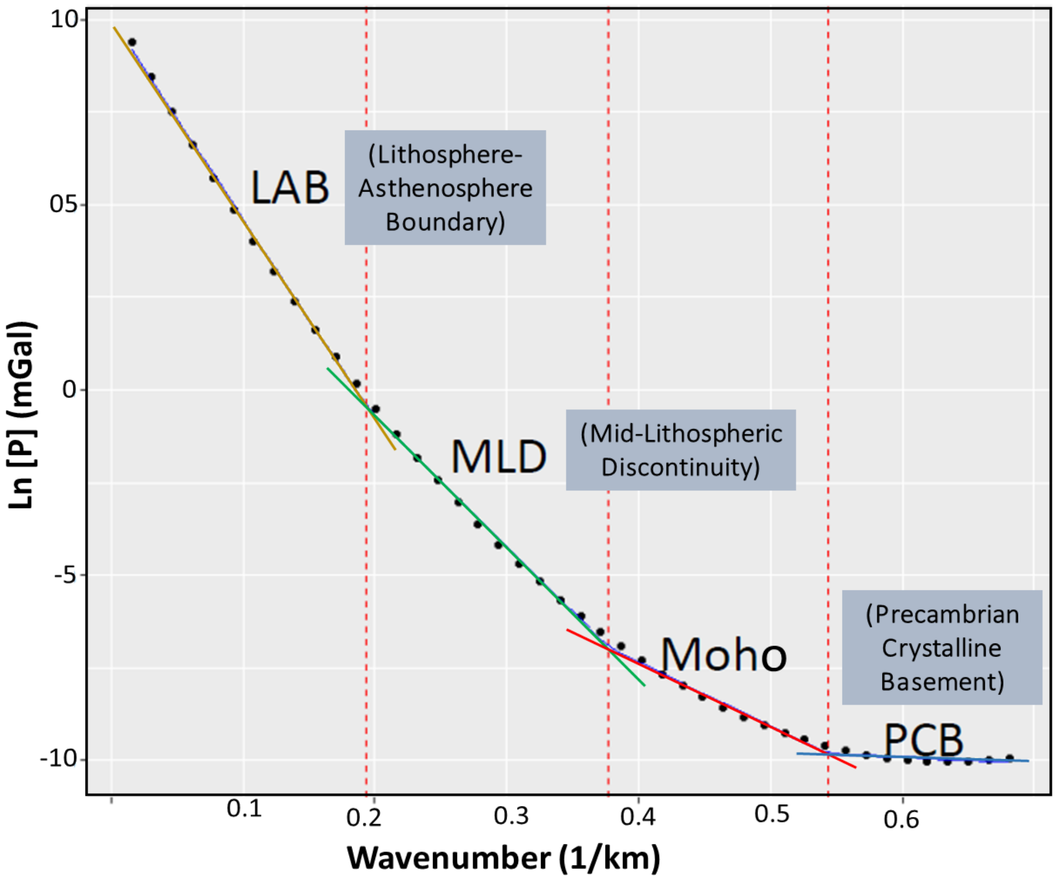

Figure 3.2: Linear segment identification using Spectral Analysis with Piecewise Regression (SAPR) within 2D radially power spectrum curve representing different density discontinuity (Emishaw et al., 2022).

However, measuring the interface of the density contrast by best fitting the straight lines remains a major concerning issue of the spectral curve analysis. A function-built procedure of Excel LINEST was implemented to avoid the dilemma of how the slope break of linear segments of the spectrum curve is defined for each linear segment. Spectral analysis with piecewise regression approach (SAPRA) was introduced to deal with the uncertainty of slope break between the linear segments of the spectrum curve, which can be defined through unique data points. SAPR is a regression analysis that partitions independent variables into intervals, and each interval can correspond with a best-fit regression line. This regression process allows the method to enhance the data as a result of which the slope splits a linear segment of the spectrum curve (Tome and Mirande, 2004; McZgee et al., 1970). During the data analysis for this study, four 1st-order multinomial fits were generated to make straight lines. Each line's average slope was addressed to determine the Moho. Afterwards, the calculation of the standard deviation was carried out for every fit in order to assess the level of error in estimating the Moho.

Three 2D forward models A - A’, B - B’, and C - C’ were generated from the WGM2012 data consisting of ORZ-KRZ, ORZ, and KRZ, respectively. The purposes of the model are to evaluate the cross-sectional profile for the rift areas to the surrounding extensional structures and to validate the depth of Moho. The constructed model ORZ (B-B’) ran 700 km across the Okavango rift area extracted from 18°30'S, 21°00'E to 21°30'S, 25°30'E. The KRZ model (C-C’) ran 300 km across the Kafue rift area extracted from 14°30'S, 25°00'E to 17°00'S, 28°30'E showing a similar orientation to the ORZ model. The ORZ-KRZ (A-A’) model ran 1000 km, with a nearly perpendicular orientation of the other two models, which was extracted from 21°00'S, 22°30'E to 14°30'S, 27°30'E. These models were executed using the 2D GMSYS module of the Geosoft Oasis Montaj software. The models used 2.67 gm/cc, 2.94 gm/cc, and 3.34 gm/cc density values for upper and lower crust, and SCLM, respectively. SCLM was assigned a comparatively lower value (3.10 gm/cc) for the partial melt area. The gravity match error for the observed and calculated profile was about 6-8% for these models.

CHAPTER IV

RESULTS

4.1. Results from the 2D Radially averaged Power Spectrum Analysis:

The Moho and Precambrian crystalline basement boundary depth for each sub-region were calculated and plotted. A few examples from the Kafue and Okavango rift zones are in (Figure 4.1). The Moho depth analysis from SAPR shows the crustal thickness varies between 26 - 36 km for the Kafue rift zone. The findings also indicate the depth of the mid-crustal discontinuity is between 10 km to 15 km.

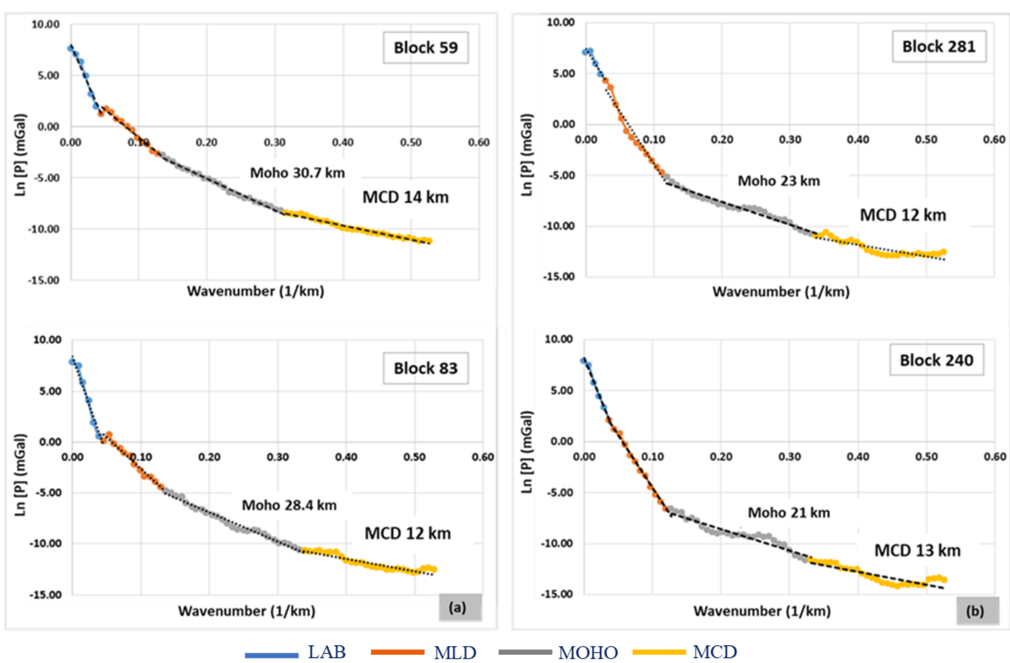

Figure 4.1: 2D radially spectrum curve showing Moho and Mid-crustal discontinuity depth around the Kafue rift zone (a) and the Okavango rift zone (b).

However, the northeastern area shows a shallower Moho depth, around 40 km. On contrary, the Okavango rift zone crustal thickness varies between 20 km to 32 km. However, the result shows the shallowest depth of Moho at around 17 km at the central part. This shallow Moho depth gradually increases towards the northeast at around 32 km. The Precambrian crystalline basement boundary indicates the shallowest depth ranges between 12 - 18 km at the basin center.

4.2 Results from the depth map of Moho, Mid Crustal Discontinuity, and Average PCB depth:

The study applied SAPR technique on 437 sub-windows measuring 1°x1° of the gravity anomalies taken from WGM-2012. These sub-windows covered the Okavango Rift Zone (ORZ), Kafue Rift Zone (KRZ), and the adjacent regions, to calculate the depths of the Moho, mid-crustal discontinuity, and the PCB average depth. Resulted Moho depth map from the SAPR analysis showed the depth of Moho through the study area ranges from 20 and 40 km. Moho depth was observed shallowest between 19 and 27 km in the southwest region of the ORZ (Figure 4.2). The shallowest pattern continues NE toward the Kafue rift zone with moho depth ranges from 28-32 km. This thin Moho gradually thickens as it approaches cratonic areas, such as the Zimbabwe, Kaapvaal to the southeast, Kalahari to the southwest, and the Congo to the west side of the study area, which reach a thickness of 37–42 km.

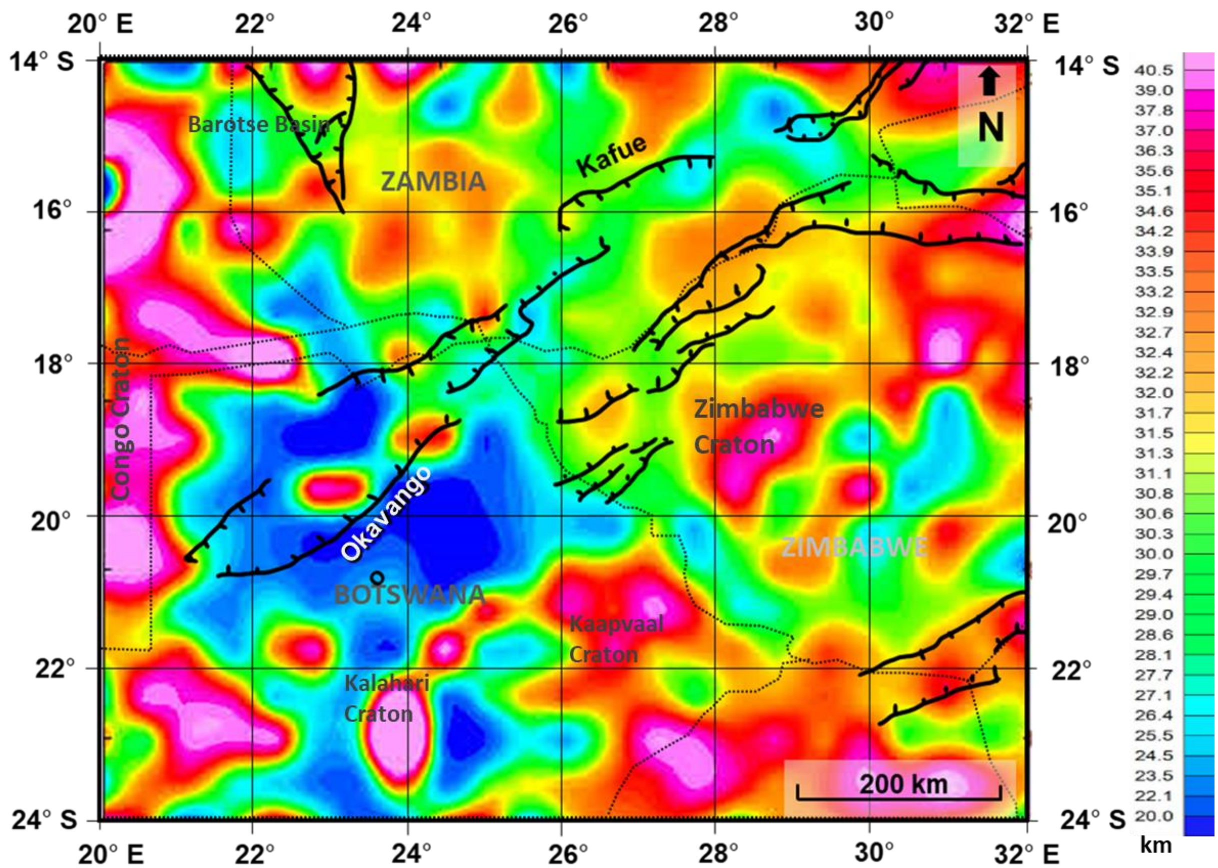

Figure 4.2: The map showing the depth of the Moho of the study area indicating shallowing Moho depth for the rift area compared to the surrounding cratonic area.

The SAPR Mid Crustal Discontinuity map (Figure 4.3) shows the MCD depth ranges as of 10-19 km for the study area, indicating a shallower depth towards the rift system and a deeper depth towards the cratonic area. The Mid-Crustal Discontinuity for the ORZ and KRZ was around 10 - 13.3 km, and 12.1 - 14.1 km, respectively.

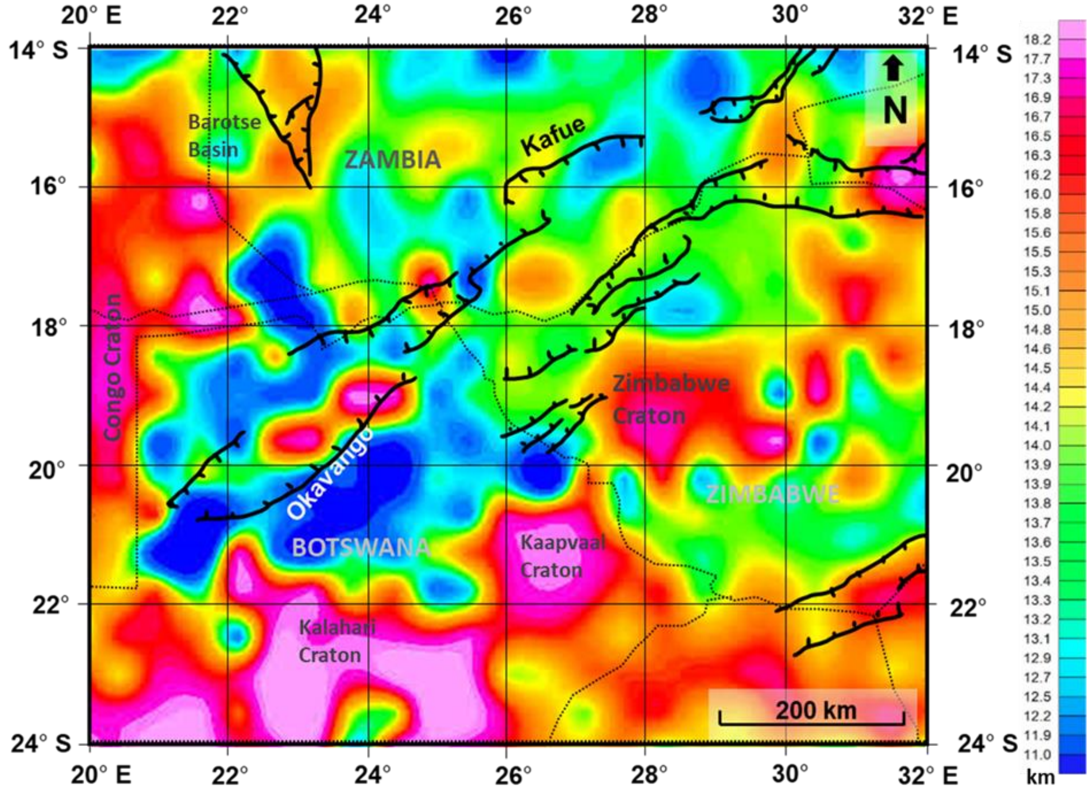

Figure 4.3. Map Showing the MCD depth information of the study area. Like the Moho depth map, the pink zone implies the deeper MCD depths, and the blue attribute displays the lesser MCD depths.

The depth of the Mid Crustal Discontinuity was scaled by 4Pi to estimate the Average PCB depth. According to the SAPR basement map (Figure 4.4), the depths are more shallow in the rift zone but become deeper as they approach the PCB in the cratonic area. SAPR findings indicate that the depth beneath the ORZ, KRZ, and nearby volcanic rocks of quaternary time to reach Precambrian crystalline basement ranges from 0.9-1.5 km. This pattern of depth matches that of the Moho and Conrad Boundary.

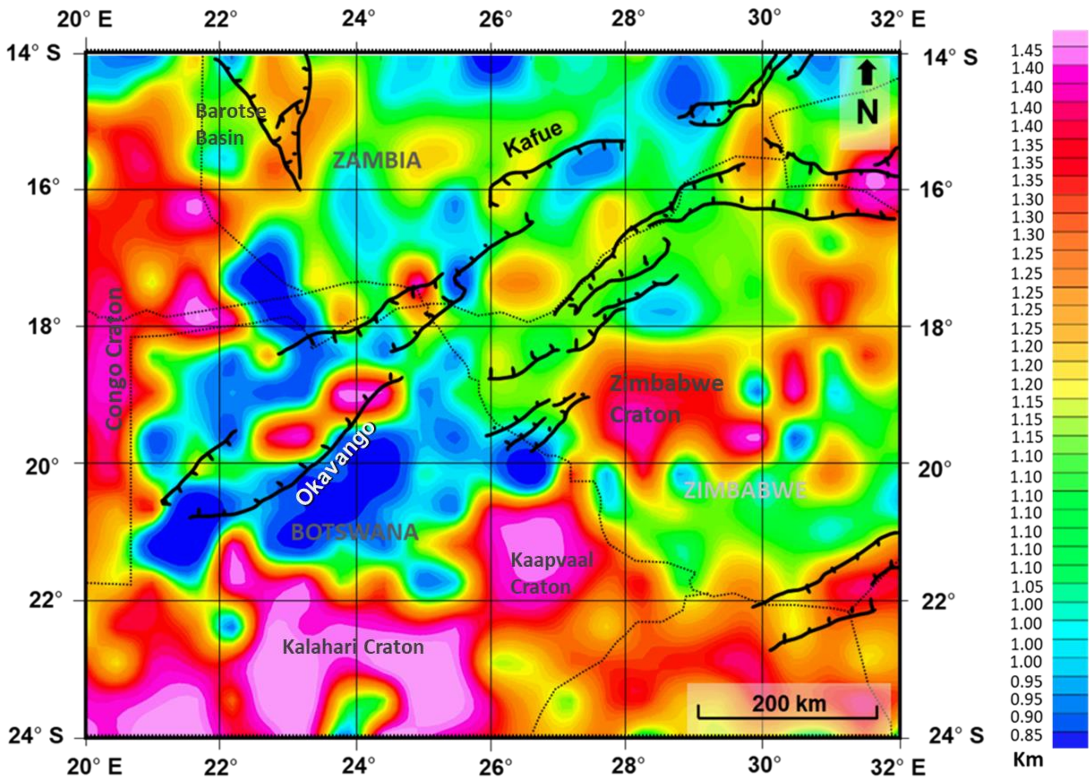

Figure 4.4. Map Indicating the Average PCB depths information under the OKZ, KRZ, and surroundings. Like Moho and MCD depth maps, this map also shows a similar pattern. The blue area suggests the shallower PCB depths, and the pink area displays the greater ones.

4.3 Results from the 2D Forward Models:

The Moho depth, as calculated by 2-D gravity forward modeling (Figure 4.5) are similar to those found from 2-D power spectrum curve. This similarity is evident in areas located beneath the ORZ and towards the southwest of KRZ. The Moho profile is elevated and has a regional arching structure within the range of 19°00'S - 21°00'S and 22°00'E - 23°30'E. The shallowest depth of this profile is 25 km, and it is directly located beneath the Okavango Rift Zone. This 2D gravity anomaly zone was delineated in ORZ (B-B') and ORZ-KRZ (A-A') 2D Forward models (Figure 4.5). A similar Moho profile was also delineated, ranging from 15°00'S - 16°30'S and 23°30'E - 28°00'E with the shallowest depth of 28 km beneath the Kafue rift zone. Both the KRZ (C-C') and ORZ-KRZ (A-A') forward models exhibit this 2D gravity anomaly zone (Figure 4.5). According to these models, the average thickness of the crust is 28-32 km in the ORZ, KRZ, and nearby regions. The 2D forward gravity model indicates the upper and lower crust boundaries are within a range of 12 to 19 km.

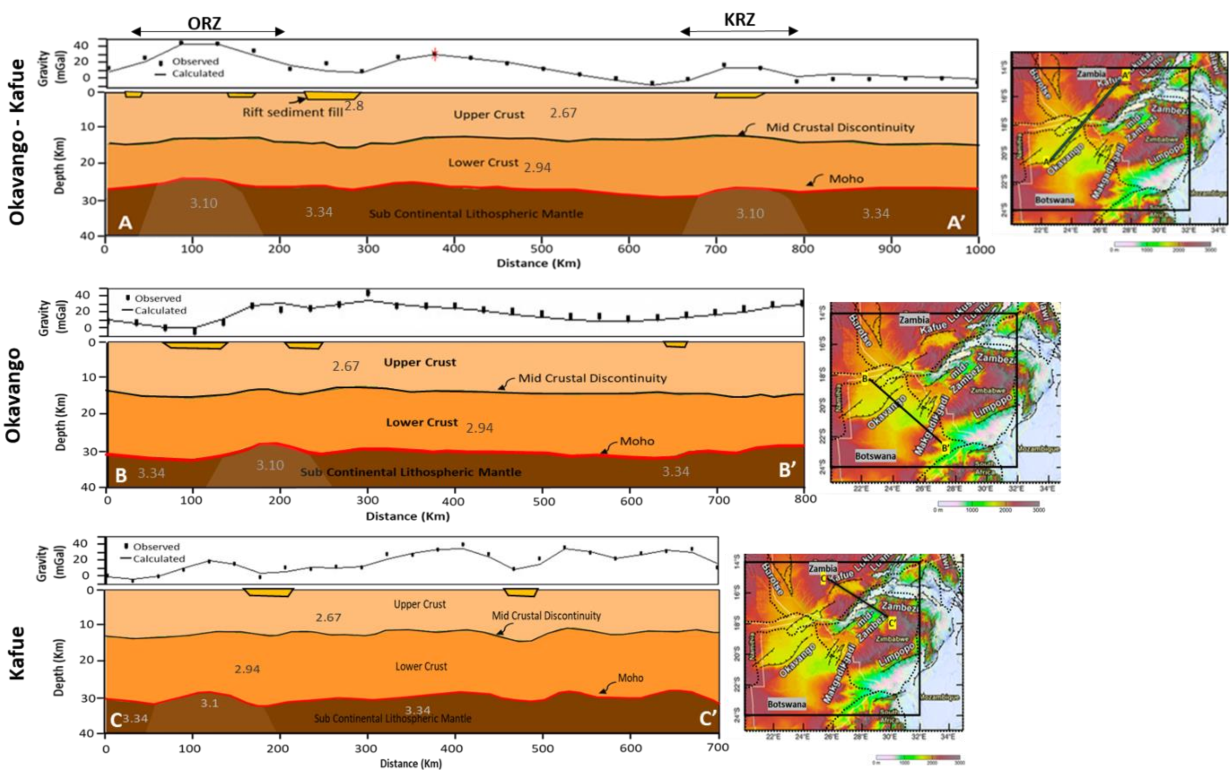

Figure 4.5: 2D forward gravity models showing Idealized NE-SW geological cross-section from Okavango to Kafue rift zone (A-A') and NW-SE cross-section B-B' and C-C' along Okavango and Kafue rift zone, respectively.

CHAPTER V

DISCUSSION

The imaging of the lithospheric formation below the Precambrian basement using SAPR technology has attracted considerable attention as a means to improve our comprehension of the impact of tectonic forces on it. Spectral analysis from 2D gravity data can image subsurface structures with the major advantage of uniform aerial coverage for a vast area (Emishaw and Abdelsalam, 2023). Unlike other traditional geophysical methods, the SAPR technique can provide subsurface imaging for any terrain despite its accessibility. This study primarily aimed to use spectral analysis of 2D gravity anomalies data to characterize the lithospheric structure. The key objectives were to map the depths of the Moho, Mid-crustal discontinuity, and Precambrian basement beneath the ORZ and KRZ.

This study aimed to evaluate the practicality of the conceptual model in determining the depths of the Moho, Mid-crustal Discontinuity, and potential variations in composition of the subcontinental lithospheric mantle beneath the ORZ and KRZ by generating 2D forward gravity models. Gravity models are nonunique in nature; hence, substantial models were constrained, incorporating numerous factors like rock mass density and lateral variability. The 2D forward gravity models incorporated information on crustal thickness and mid-crustal discontinuity thickness, which were derived from the data obtained through spectrum analysis.

In order to address the distinct lithology for the Damara, Magondi, and Ghanzi-Chobe Mountain belts with the sediment buildup in Karoo basins, the ORZ model was augmented with upper crustal masses of varying properties like densities (Mapeo et al., 2006; Singletary et al., 2003). The upper crust model used 2.67 g/cm3 of density, which is a suitable representation of the predominant granitic or gneissic composition found in southeastern Kaapvaal Craton, Magondi Belt, and Zimbabwe cratonic block.

The shallowest depth of Moho determined from the 2D gravity forward model beneath the Okavango and Kafue rift zone area indicates crustal thinning and domed sub-continental lithospheric mantle beneath these rift systems. The phenomenon of Moho shallowing resulting from crustal thinning is a common feature observed in different continental rifts (Birt et al., 1997). Besides, the gravity analysis, along with the spectral analysis, indicates a continuation of a similar signature from ORZ towards the Kafue. The ORZ and KRZ have a symmetric Bouguer gravity low as evidenced by their gravity signature, with anomalies ranging from 20 to 25 mGal at the rifts' center to 10 to 30 mGal at their boundaries. The simplest way to represent this gravity signature is to include a somewhat lighter (3.10 gm/cm3) density and is surrounded by a standard mantle that is 3.34 gm/cm3 denser.

In this study, the outcome of 2D gravity forward model was compared with a previous study conducted by Yu et al. in 2015 (Figure 5.1a). Both the results showed shallowing Moho beneath the Okavango rift zone indicating low-density mantle lithosphere and crustal thinning under the Okavango rift zone (Figure 5.1b). One possible explanation could be lithospheric stretching causing partial melting associated with the incipient rift. According to the geophysical investigation conducted by Yu et al. in 2015, the symmetric doming feature located at the center of the rift axis, as shown in Figure 5.1, suggests that the Moho is uplifted beneath the rift system, indicating the presence of a pure shear extension-type rift system. (McKenzie, 1978).

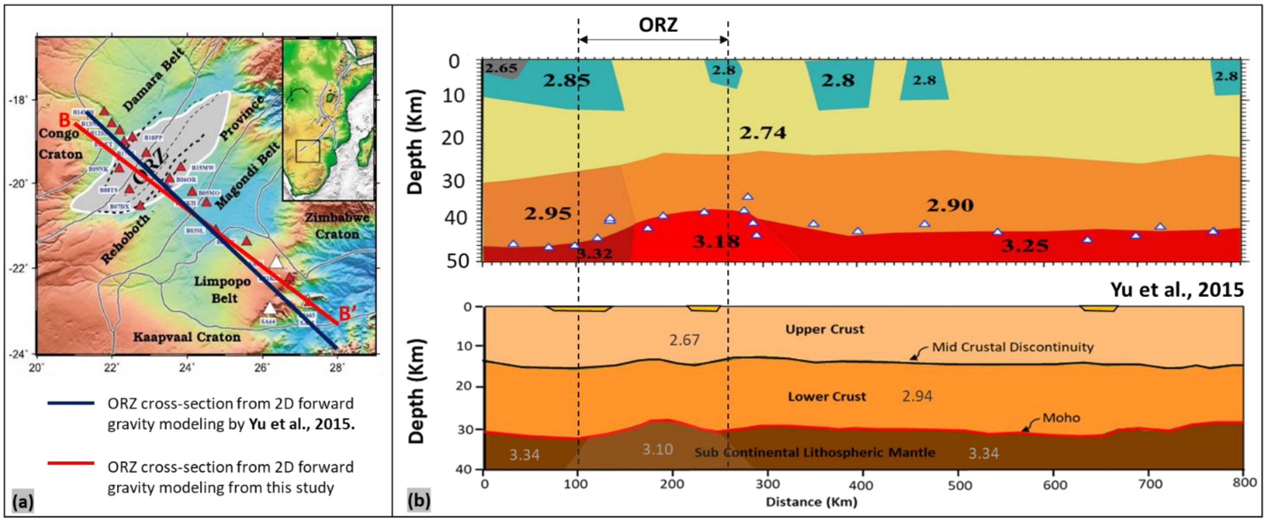

Figure 5.1: (a) locations of the 2D forward gravity models showing Idealized NE-SW geological cross-section from Okavango to Kafue rift zone. The red (B-B') and the blue line show the cross-section trending NW-SE along ORZ from this study and Yu et al., 2015, respectively.

However, both models showed nearly 6-10 km difference in depth estimation for the Moho. These discrepancies may correspond to several factors and limitations while generating the models. Both studies assigned density values for different lithospheric boundaries like sub continental lithospheric mantle, lower crust, and upper crust. However, these values were not calibrated with any in-situ measurement. These values were used based on the 2D forward gravity model performed by other studies at similar tectonic settings (Matende et al., 2020, Fletcher et al., 2018Demissie et al., 2018, Leseane et al., 2015). According to the model used in the study, the amount of sediment filling the rift in the study area is estimated to be between 1 and 2 kilometers. This value was constrained by different literature that mentioned the sedimentary deposition thickness of a maximum of 2 km surrounding the area of ORZ (Leseane et al. 2015; Yu et al, 2015). Despite these system limitations, this observation is in good agreement with the result of other rift system studies, i.e., the Okavango rift system by Yu et al., 2015; and Gao et al., 2004. Once the rift development begins, additional volcanic activity and related activities can be detected along the Okavango rift zone, which continues towards the Kafue rift zone. Comparable volcano-related events have been observed in other continental rifts, such as Kenya and Rio Grande rift, as noted by Biggs et al. in 2009 and Perkins and Anthony in 2011.

McKenzie's pure shear model, proposed in 1978, was predicated on the notion that crustal thinning occurs uniformly and abruptly, leading to changes in both thermal and gravitational conditions. Plate boundary stresses, tensional stresses, and frictional forces are among the driving factors behind this model. Pure shear happens when a material is uniformly stretched and thinned in two perpendicular directions, leading to a transformation in shape without a change in volume. McKenzie introduced a stretching factor (beta factor) which is the ratio between initial width of the stretch domain and the width of the stretched domain. This study interpreted that the Earth's crust has undergone stretching and thinning in a northeast-southwest direction below the Okavango rift zone, resulting the crustal extension. The brittle extension on the upper crust causes a series of normal faults and emergence of a rift valley (Figure 5.2). The lower crust undergoes ductile extension while the Moho experiences shallowing due to partial melting beneath the sub-continental lithospheric mantle. This type of stretching aligns with the pure shear model since there is uniform stretching and thinning of the crust in a horizontal orientation.

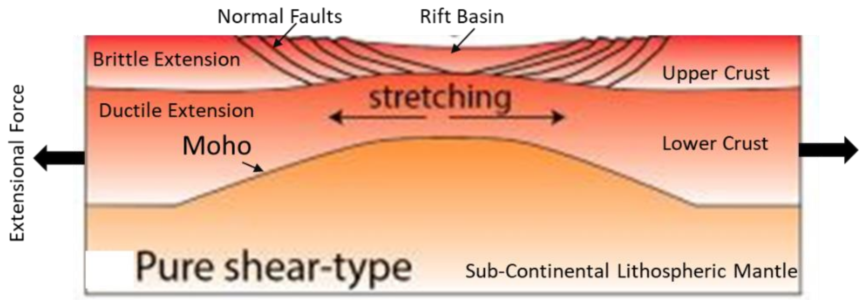

Figure 5.2: Schematic representation of a simplified uniform stretching model by McKenzie (1978) showing crustal thinning and stretching.

McKenzie (1978) proposed that extensional basins are formed by either pure shear or simple shear, depending on the orientation of the principal axes of strain. The orientation of the Okavango rift and the faults are roughly perpendicular to the direction of extension which is consistent with pure shear model. The observations and analyses from numerous geological studies and evidence also support this interpretation. Buck (2006) states that the faults in the Okavango Rift Zone are approximately at a right angle to the extension direction. According to Ebinger et al. in 1997, the rift basin's form is stretched lengthwise in the extension direction, whereas a simple shear model would produce a more intricate and uneven basin shape. As per Chorowicz's statement in 2005, there is proof of fault blocks on both sides of the Okavango rift basin rotating around a vertical axis. Bastow et al., 2010 mentioned that there is a greater extent of horizontal displacement along the faults of the Okavango Rift Zone in comparison to the vertical displacement. Study by Ebinger (1989) mentioned the presence of strain markers like slickensides suggesting the deformation in the ORZ has been primarily horizontal which is consistent with the pure shear model. Besides, the beta factor value of 1.2 to 1.5 estimated for the Okavango Rift System (Ebinger & Lamb, 2019; Schofield & Cowie, 2019) suggests that the rift has undergone significant extension relative to its width which is consistent with the development of a wide rift basin through pure shear deformation.

The mid-crustal discontinuity exhibits shallowing signature similar to the Moho beneath the Okavango and Kafue rift zones. Based on the 2D forward gravity model and spectral analysis conducted in the study area, the mid-crustal discontinuity was found to be between 9 to 15 km in depth, indicating that it may be the Conrad boundary separating the upper and lower crust. However, further evidence from other studies, i.e., seismic, is required to confirm this interpretation.

To summarize, the configuration of the crustal structure underneath Okavango and Kafue rifts was represented using gravity modeling. The resulting crustal thinning and infilling by low-density mantle due to partial melting beneath the ORZ and KRZ indicate the continuation between these two rift zones. The low level of crustal stretching is often associated with a passive rifting model suggesting the initiation of these rift systems due to transtentional movement between cratonic blocks along ancient orogenic belts (Yu et al., 2015). This interpretation acknowledges crucial information regarding the rift system evolution as well as the crustal composition, variability, and modification influenced by the rifting process of EARS. The depth of both the Moho and mid-crustal discontinuity is similar to that determined by 2D power spectral analysis, specifically in the Okavango Rift Zone (ORZ), Kafue Rift Zone (KRZ), and the region located to its southwest to northeast. (Figure 4.1, 4.2, and 4.3).

CHAPTER VI

CONCLUSION

The aim of this study was to employ geophysical imaging techniques to estimate the depths of the Moho, MCD, and PCB underneath the Okavango Rift Zone located in the north-western region of Botswana, as well as the Kafue Rift Zone situated in Zambia. The WGM 2012 Bouguer gravity anomalies were employed to generate a 2D forward gravity model as well as perform spectral analysis. The results show that ORZ has the depth of Moho about 20 - 32 km, and this shallow depth pattern continues towards the NE part, in which the Moho depth arrives at 28-32 km under the Kafue Rift Zone. The study identified a zone of reduced thickness between the boundaries of the upper crust and lower crust, referred as the Mid-Crustal Discontinuity (MCD) or Conrad Discontinuity. This zone was observed beneath the ORZ which extended towards the KRZ, with depths ranging from 10-14 km beneath the ORZ and 12-14 km beneath the KRZ. This investigation indicates that the SAPR could possibly image the Conrad Discontinuity within the continental crust. The shallowing Moho depth delineated by the 2D forward gravity model satisfies the pure shear extension type rift system followed by crustal thinning and partial melting beneath the ORZ and KRZ. The findings of this study suggest that mantle flow acting a substantial role in the formation of a narrow rift in the East African Rift System and may assert implications for other rift systems as well. This study compared the Kafue Rift system and other well-developed branches of the EARS, creating a more comprehensive model for the rift systems.

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VITA

FARJANA MONSUR MILY

Candidate for the Degree of

Master of Science

Thesis: DETERMINATION OF MOHO DEPTH BENEATH THE OKAVANGO AND KAFUE RIFT USING SPECTRAL ANALYSIS WITH PIECEWISE REGRESSION (SAPR) OF SATELLITE GRAVITY DATA

Major Field: Geology

Biographical:

Education:

Completed the requirements for the Master of Science in Geology at Oklahoma State University, Stillwater, Oklahoma, in May 2023.

Completed the requirements for the Master of Science in Geophysics at the University of Dhaka, Bangladesh, in April 2017.

Completed the requirements for the Bachelor of Science in Geology at the University of Dhaka, Bangladesh, in May 2015.

Experiences:

- Journal Editor in Chief - Microbiology & Writing Center partnership, OSU | May 2023
- Consultant - Writing Center, Oklahoma State University | 2022 - 2023
- Graduate Research Associate - Boone Pickens School of Geology, OSU | 2021 - 2022
- Graduate Teaching Associate - Boone Pickens School of Geology, OSU | 2021 - 2022

Publication:

Mily, F., Abdelsalam, M., (2023). Imaging the Moho and Conrad Crustal Discontinuity Using the Spectral Analysis with Piecewise Regression of Gravity Data. [Abstract] In Geological Society of America, Volume 55, No. 1, doi: 10.1130/abs/2023SC-385502.

Technical Skills:

ENVI, ArcGIS, Oasis Montaj, Petrel, Petromod, Google Earth, MS Office.

Professional Affiliation:

GSA, AWG, TGS