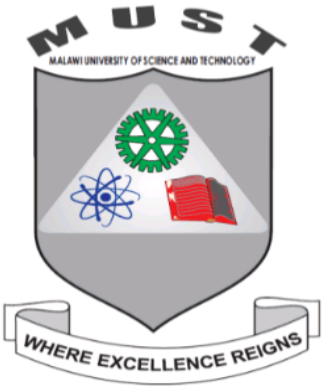


TECTONIC CONFIGURATION OF THE MALAWI RIFT REVEALED FROM CRUSTAL THICKNESS MODEL

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DISSERTATION SUBMITTED TO NDATA SCHOOL OF CLIMATE AND EARTH SCIENCES OF THE
MALAWI UNIVERSITY OF SCIENCE AND TECHNOLOGY IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE BACHELOR OF SCIENCE DEGREE IN EARTH SCIENCE

July 2021

DECLARATION

I Luzana Kamtangwala declare that this research project represents my work and that it has never been submitted to this institution or any other institution for any academic purpose. All sources of information have been appropriately acknowledged.

Signature

Date 2 June 2021

DISSERTATION APPROVED BY:

SUPERVISOR:

Title, Initials, Name: Signature: _____

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ABSTRACT

In this study, a crustal thickness model of the Malawi rift is created from the inversion of the EIGEN-6C4 global gravity model. The regularized inversion based on the Gauss-Newton formulation of Bott's equation is employed to resolve the Moho topography. The inversion process uses tesseroids to account for the earth's curvature. Moho depth modeling for such a massive landmass cannot ignore the earth's curvature. The Bouguer effect, terrain effect, and gravity effect due to sediments are also corrected and

calculated in a spherical approximation. The resulting crustal thickness model was validated seismolog

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Firstly, I would like to express my deep and sincere gratitude to my research supervisor, Dr C. Chisenga for providing invaluable guidance throughout this research. His dynamism, vision, sincerity and motivation have deeply inspired me. Guiding me through the way and trusting my capabilities to handle this study. It was a great privilege and honour to work and study under his guidance. I would also like to thank him for his empathy, great sense of humour, patience and insightful feedback that pushed me to sharpen my thinking during the discussion during my research work and dissertation preparation, completion and success.

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My thanks go to all the people who have supported me to complete the research work directly or indirectly. I also would like to thank everyone who negatively contributed during this study, it helped me rebuild myself and grow stronger whilst hoping for a greater end. Above all, The Almighty God, through His love and grace, predestined my academic journey which today I cherish. Thanks.

DEDICATION

To the birth of my Breath; Maxwell Kamtangwala (Father) and Ellen Magaleta (Mother), my sisters and daughter (Peace) and the best friend of all times Innocent Misinde.

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ACRONYMS/ABBREVIATIONS

EARS- East African Rift System

TRM- Tanganyika-Rukwa-Malawi

LAB- Lithosphere-asthenosphere boundary

EDC - Edge-driven convection

MRZ- Malawi Rift Zone

SAFARI- Seismic Arrays for Africa Rift Initiation

EIGEN-6C4 - European Improved Gravity Model of the Earth by New Techniques

ICGEM - International Centre for Global Earth models website

GRACE- Gravity Recovery and Climate Experiment

GOCE- Gravity field and steady-state Ocean Circulation Explorer

EGM2008 -Earth Gravity Model 2008

ESA - European Space Agency

GLQ- Gauss-Legendre quadrature

SGG- Satellite Gravity Gradiometry

SST- Satellite-to-Satellite Tracking

GPS- Global Positioning System

TRM- Tanzania-Rukwa-Malawi

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CHAPTER 1

1.0 INTRODUCTION

1.1 Background

The study of solid earth geophysics is essential to comprehension of the earth's subsurface and interior, hence the principal origin of information of the lithosphere (Slejko, 2019). This knowledge is extracted from measurements carried out mostly on the land and sea surface of our planet, but also at various heights with aircraft or satellites and below the surface through perforations. From these measures, information is derived on the phenomena and the knowledge of geometry and physical parameters of the various bodies constituting the Earth. Geodynamics and tectonics activities of the earth are lithospheric activities.

This study utilizes geophysics to analyze tectonic activities along the Malawi Rift which is in the western branch of the East African Rift System. A few crustal thickness studies have been carried in Africa preventing the geoscientific community from doing detailed Crustal and upper mantle modelling using seismology or any geophysical data since the crustal thickness is a crucial parameter for such a modelling approach (Meijde & Nyblade, 2013).

The East African Rift System (EARS) is a natural testbed for studies of active continental extension Ebinger C. J., (2012) and Njinju, et al., (2019). The rift is traditionally is interpreted to be composed of two distinct segments: an older, volcanically active eastern branch and a younger, less volcanic western branch (Macgregor, 2014). The EARS which runs through the northern to southern Malawi is the largest seismically active rift system on Earth in which deep seismicity is localized along or near major border faults, while relatively shallower seismicity is mostly associated with strain localization within the rift axis (Shillington, et al., 2020), (Danley, et al., 2012). On a continental scale, the stress field of the EARS is governed by mantle buoyancy forces, which drive plate motions and generate dynamic topography; viscous

resisting tractions in the plate and mantle; and the gravitational potential energy due to the structure of

The Moho delineates the boundary between crust and mantle (Lewis, 1983), and this interface can be imaged accurately through deep seismic profiling, but economic considerations make gravity modelling a more practical approach for mapping crustal thickness over regional scales (Bai, et al., 2014).

Until now there have not been more geophysical comprehensive studies focusing on crustal thickness modelling of the entire Malawi Rift system. More recently (2002–2020), geophysical techniques have been used to observe several rifting episodes in the EARS, including the eruptions from the Western Branch; the Nyiragongo and Nyamuragira, Eastern Branch; Oldoinyo Lengai, and Afar Dabbahu-Manda Harraro, Erte Ale, Alu-Dalafilla and Nabro.

According to Ghomsi & Nouayou, (2020) and Chisenga & Yan,(2019) knowledge, crustal thickness variations provides a crucial constraint to geodynamic and geophysical modelling helping to identify areas for further studies. Crustal thickness models provide details and information on crustal evolution, lithological variations, and subsurface tectonic processes (Chisenga, et al., 2020). Crustal thickness is a critical parameter for understanding the processes of continental rifting and breakup and the evolution of petroleum systems within passive margins. To create crustal thickness, model the study employs an inversion of the corrected gravity data using the regularized Bott's inversion method in spherical approximation and constrained the results by seismic observations the Moho's depth varies depending on geographical location.

1.2 Study Rationale

This study aims at interpreting the geodynamics of the Malawi rift by modelling the crustal thickness using data extracted from EIGEN-6C4. The tectonics along the Malawi rift will be depicted through the crustal thickness model. Literature reveals that attempts have been done to create a crustal thickness model of Malawi Rift at the regional scale and low resolution but tectonics of the Malawi rift is still unclear (Borrego, et al., 2018), (Delvaus & Fernandez-Alonso, 2009), Branchu, et al., (2005), (Ebinger, et al., 1993),

(Castings, 1991). Information of the crustal structure beneath the Malawi Rift will improve the understa

1.3 Study Objectives

I. Aim

The main objective of this study is to interpret the geodynamics of the Malawi rift by modelling the crustal thickness using data extracted from EIGEN-6C4.

II. Specific objectives

The proposed research work has the following specific objectives: -

1. To create a crustal thickness model of the Malawi Rift.
2. To identify the tectonic provinces along and surrounding the Malawi Rift.
3. To improve the understanding of the geodynamics of the Malawi Rift.

1.4 Research Questions

1. What improvements will the crustal thickness model have on geology studies of Malawi?
2. How good is the crustal thickness model to explain the geodynamic process and tectonic evolution of the Malawi rift?
3. What relationship does the crustal thickness model have to the geodynamic processes?

1.5 Scientific significance

This study will produce information that will be used by geologists, engineers, environmental specialists and government officials on different activities and projects in Malawi. Crustal thickness varies significantly across continental margins, and mapping these variations are important for understanding continental rifting processes. Understanding the amount and location of crustal thinning beneath and surrounding the Malawi rift is also important for evaluating models of crustal extension and identifying where strain is being localized during the rifting process. Competing models for extension make different predictions for the distribution of stretching throughout the crust and mantle lithosphere.

1. This study has improved a detailed understanding of the geodynamic processes of the rift.
2. From an academic perspective, the generated information will be relevant in high learning institutions in the country
3. The study has generated information that will be used to understand the impact of the Malawi rift on the geological processes in Malawi.
4. This study has helped to delineate the tectonic boundaries, terranes and other tectonic terranes that are not yet discovered if any.
5. The model has helped to expose and quantify cumulative and recent faulting patterns in the rift (to some extent).
6. Publishing the results in a Journal.

CHAPTER 2

2.0 LITERATURE REVIEW

Global observations show that the crustal thickness varies through the tectonic regions. The continental crust is 30-70km thick having a density of 2.6-2.7 g/cm3 while the oceanic crustal thickness is 6-12km with a density ranging from 2.8g/cm3 to 3.0g/cm3.

Some previous studies in the study area have reported estimates of Moho depth, Poison's ratio and secondary velocity for the Precambrian terranes by modelling a

combination of the teleseismic receiver functions and Rayleigh wave depression and have commented

The crustal structure of the Malawi and Luangwa rift zones and adjacent areas was studied using seismic data recorded by 33 Seismic Arrays for Africa Rift Initiation (SAFARI) broadband seismic stations which are installed in the vicinity of the zones. The southern region of Malawi has a possibility of partial crustal melting, elevated temperatures or fluid-filled deep crustal faults that are likely associated with the lithospheric stretching. The Northern has a consistent low stretching factor with a general absence of volcanism in the Malawi Rift Zone (MRZ), (Sun, et al., 2020).

Rifting has had an evident effect on the geomorphology of East Africa and is always correlated with enormous volcanism (Scoon, 2018). Despite being considered morphologically well developed the Malawi Rift segment has only isolated zones of magmatism (Njinju, et al., 2019). Wadge, et al., (2016) studied volcanism in the EARS improving the understanding of roles of crustal stress through the application of seismic theories focusing on stress and strain.

To determine the extent to which the crust has been modified by Cenozoic rifting and magmatism teleseismic earthquake recorded of SEGeNT broadband seismic stations data is studied applying a similar approach as Kachingwe, et al., (2015) and (Borrego, et al., 2018). Njinju, et al., (2019) used gravity data, 2D radially averaged power density spectrum analysis, 2D forward gravity modelling of EDC to produce Moho depth estimates, lithosphere-asthenosphere boundary (LAB) depth estimates, and EDC when investigating the lithospheric structure of the magma-poor rifting processes along the Malawi Rift.

The Northern Malawi Rift is an active early-stage rift segment that provides the opportunity to quantify cumulative and recent faulting patterns in a young rift, assess contributions of the intra-rift faults to accommodate rift opening and examine controls on spatial patterns of faulting (Shillington, et al., 2020).

This study will employ the approach by Chisenga & Yan, (2019) to interpreting the geodynamics of the Malawi rift by modelling the crustal thickness. In summary, there is

a lack of detailed research studies on the crustal thickness of the entire rift system which is part of the

CHAPTER 3

3.0 STUDY AREA

3.1 Geology and Tectonic Setting

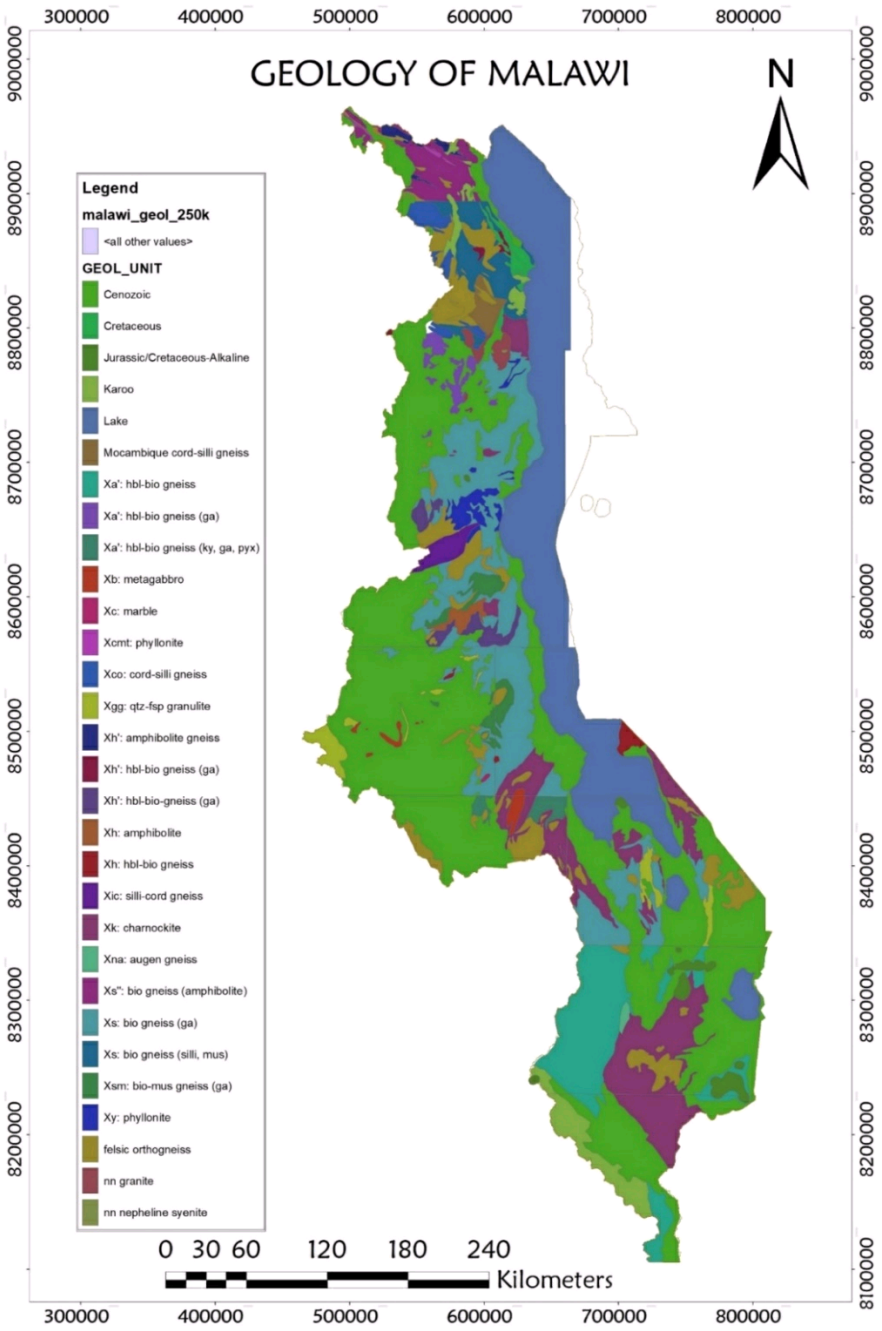


Figure 1 Geological Map of Malawi

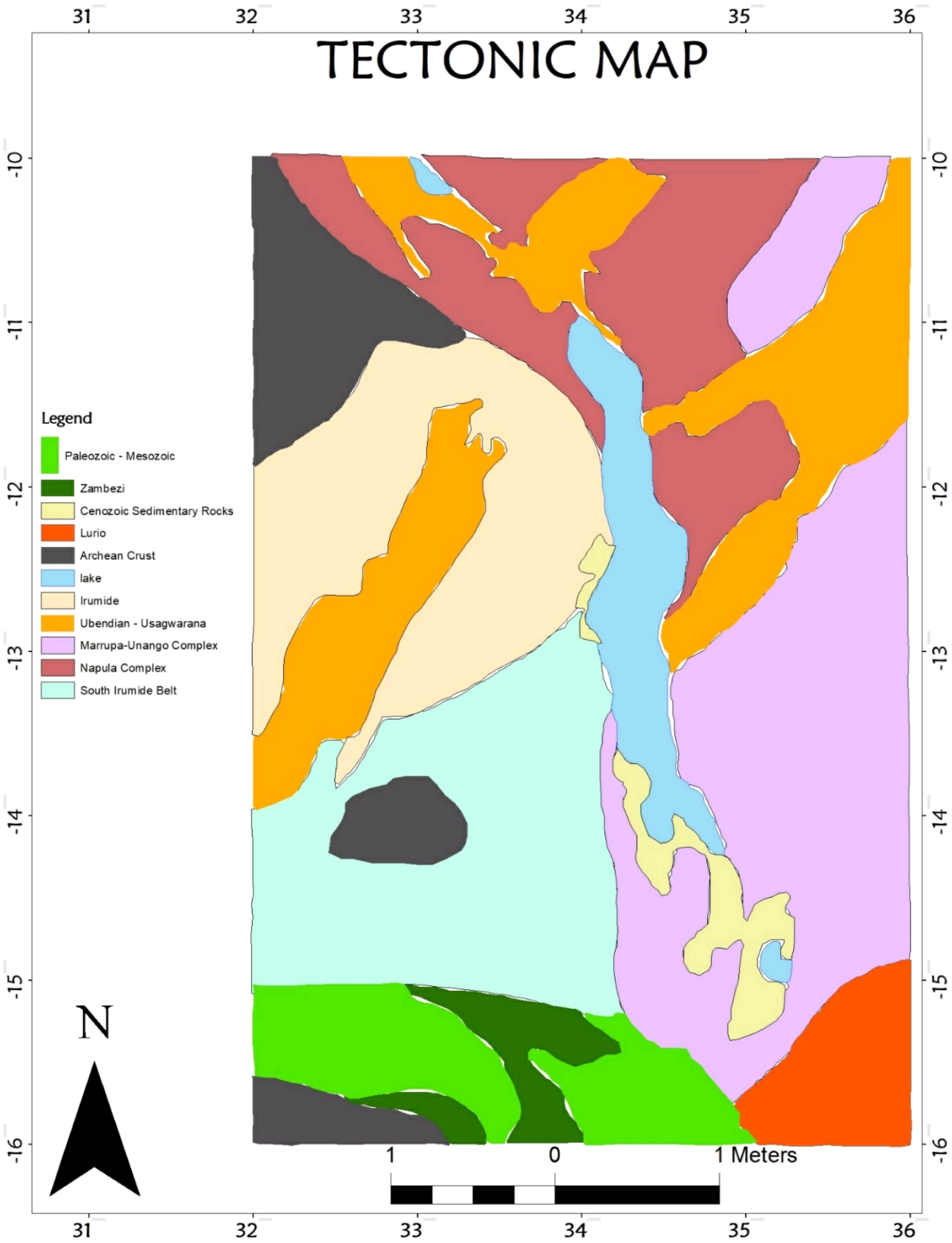

TECTONIC MAP
31
32
33
34
35
36
-10
-11
-12
-13
-14
-15
-16
Legend
Paleozoic - Mesozoic
Zambezi
Cenozoic Sedimentary Rocks
Lurio
Archean Crust
lake
Irumide
Ubendian - Usagwarana
Marrupa-Unango Complex
Napula Complex
South Irumide Belt
N
1
0
1 Meters

Figure 2 Tectonic Map

The African continent is a result of a complex greater than billion years old history from juvenile crust formation and craton stabilization in the Archean, extensive crustal reworking during the Proterozoic, Pan-African accretion followed by the Mesozoic breakup of the Gondwana accretion supercontinent and Cenozoic widespread volcanism, uplift and continental rifting. Africa is an assemblage of Precambrian cratons and fragments separated by Proterozoic and Paleozoic mobile belts. Apart from oblique conversion between Eurasian and northern Africa at 2 to 6 mm/y. The continent is surrounded by divergent plate boundaries, predefined during the Mesozoic breakup of Gondwana and the coeval opening of the southern and central Atlantic. Currently, continental breakup and rifting occurs along the boundary between the Nubian and Somalian plates, marked by the 500km long East African Rift System.

The Precambrian history of Africa can be divided in Archean crust formation and the stabilization of the first cratonic cores followed by their Proterozoic assemblage which created the surrounding collisional fold belts. The continent's core is mainly composed of the West African and Saharan Meta-craton, located in northern Africa, Congo craton, Kaapvaal plus Zimbabwe cratons and some smaller Archean fragments such as the Tanzanian and Uganda cratons and the Bangweru and Limpopo microcontinents located in Southern Africa.

Driven by the African plate extension and thinning the East African Rift System began during the Oligocene at approximately 30Ma and continued intermittently through the Miocene, Pliocene and Pleistocene into the Holocene (Scoon, 2018). The EAR system is composed of two arms. The older eastern branch which extends through the main Ethiopian rift to the Omro-Turkana lows, Kenyan rifts and ends to the north Tanzanian divergent basins in the south is more volcanically active than the younger western branch which is considered to have been initiated in an area of the thinner lithosphere with Paleoproterozoic cover in the Virunga area and has propagated northwards where it now abuts against thick carbonic lithosphere covered by a thrust belt consisting of gneisses, meta-sediments and metavolcanic of Neoarchaean to Proterozoic age. According to (Chorowicz, 2005) the western branch runs from Lake Albert in the north to

Lake Malawi in the south. The rocks of the Karoo Supergroup and newer sedimentary units deposited

Fault systems of the Tanganyika-Rukwa-Malawi (TRM) segment of the East African Rift System show evidence of repeated reactivation since the Paleo-Proterozoic, controlling successive stages of sedimentary basin formation. The evolution of the basement of the TRM rift segment started with the development of the NW-SE trending Paleo-Proterozoic, Ubende shear belt along the western margin of the Archean Tanzanian craton. This belt was repeatedly reactivated by left-lateral movements in retrograde greenschist facies during the Meso- and Neoproterozoic. A Permo-Triassic (Karoo) rift system developed in Late Carboniferous-Middle Triassic times, in response to compressional and transpressional deformations in east-central Africa. This intraplate deformation may have been induced by stress transmission through the continental lithosphere over long distances from both the southern and the northern (Neo-Tethys) margins of the Gondwana continent. Rifting was probably minor during the Late Jurassic-Cretaceous in the TRM zone, but the existence of an Early Tertiary rifting stage is highlighted. The Late Cenozoic period of rifting started 8- 9 Ma ago by semi-radial extension in the Rukwa-Malawi area. Since the middle Pleistocene, compressional intraplate stresses interfere with the evolution of the Late Cainozoic rift system. Volcanism and climatic fluctuations are, besides tectonism, additional factors that influence the sedimentary infill of the TRM rift basins (Delvaux, 2001).

As with much of East Africa, the geology of Malawi is dominated by the ongoing splitting of the African plate, which has resulted in the EARS. This stretches more than 4,000 km from Eritrea and Ethiopia in the north, where rifting initiated about 40–50 million years ago (Ma), southwards to Malawi where rifting may have commenced as recently as 8 Ma, and on into Mozambique.

The rift zone is comprised of four alternating asymmetrical half grabens and several smaller basins, resulting in three main structural and drainage basins. The earliest sediments that are associated with Cenozoic rifting in the Rungwe volcanic province, which borders the Malawi Rift to the north are associated with welded tuffs dated to 8.6Ma. The sediments are not directly correlative with sediments in the subsiding Malawi Rift. Age models based on sedimentation rates suggest that rifting commenced

between 1.7 and 12Ma. The earliest interval of rifting and subsidence in the Malawi rift probably occur

The geology of Malawi is composed of the basement complex, the Karoo system, the Chirwa Alkaline province which is of the upper Jurassic and cretaceous and also the Tertiary and Quaternary (Mines, 2009). It is part of Kibaran orogeny which formed through continental collision that constructed Rodinia as known in Africa. Malawi lies within the Usagaran belt in the northeast, the Ubendian belt to the northwest, Irumide and Mozambique belts to the southeast which ages within the late Precambrian and early Paleozoic and is dominated by the basement complex rock. The terrane is formed on extremely ancient crystalline basement rock which is composed of crystalline rocks of Precambrian to lower Paleozoic age (Ray, 1974).

3.2 Geographical Location

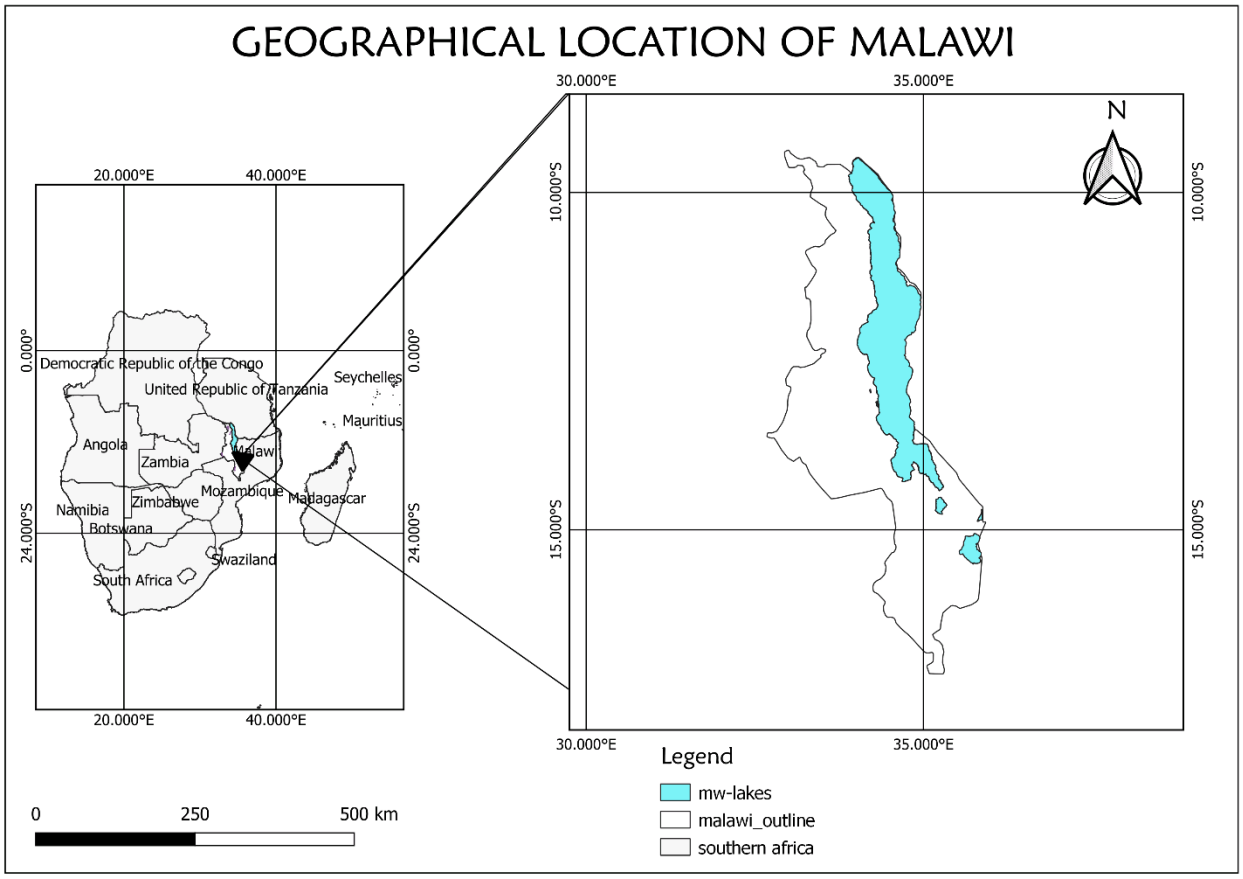


Figure 3 Geographical Location

Malawi is part of the sub-Sahara of Africa and is a landlocked country located in the southeastern part of the continent. Composed of 45,747 square miles Malawi is bordered in the north and east by Tanzania, to the east, south, and southwest by Mozambique, and the west by the nation of Zambia. Much of the land surface of Malawi is a large plateau that is between 914.4 to 1219.2 meters above sea level. Elevations rise over about 2500 meters in the Nyika Plateau, Zomba mountain approximately 2087 meters and 3002 meters Mulanje mountain. The Shire highlands in the south are the lowest area in the country with elevations extending from 609.6 to 914.4 meters.

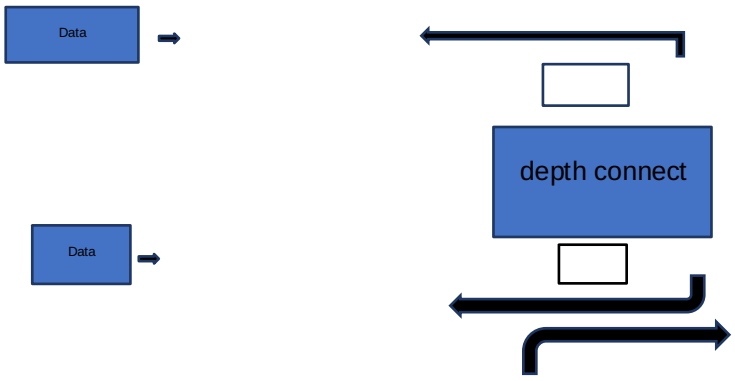
The Malawi rift which is located at the southern end of the western area of the East African Rift between 9^0 and 14^0S is the prominent example of immature rifting hence making the rift system dynamic and two-thirds of it is covered by Lake Malawi (Grijalva, et al., 2018).

CHAPTER 4

4.0 METHODOLOGY

4.1 Introduction

This chapter presents the methods materials and technical approach that were used to attain the objectives of this study. Discussed in more detail are the descriptions of the research strategy, research methods, data collection and management methods and the type of data analysis.



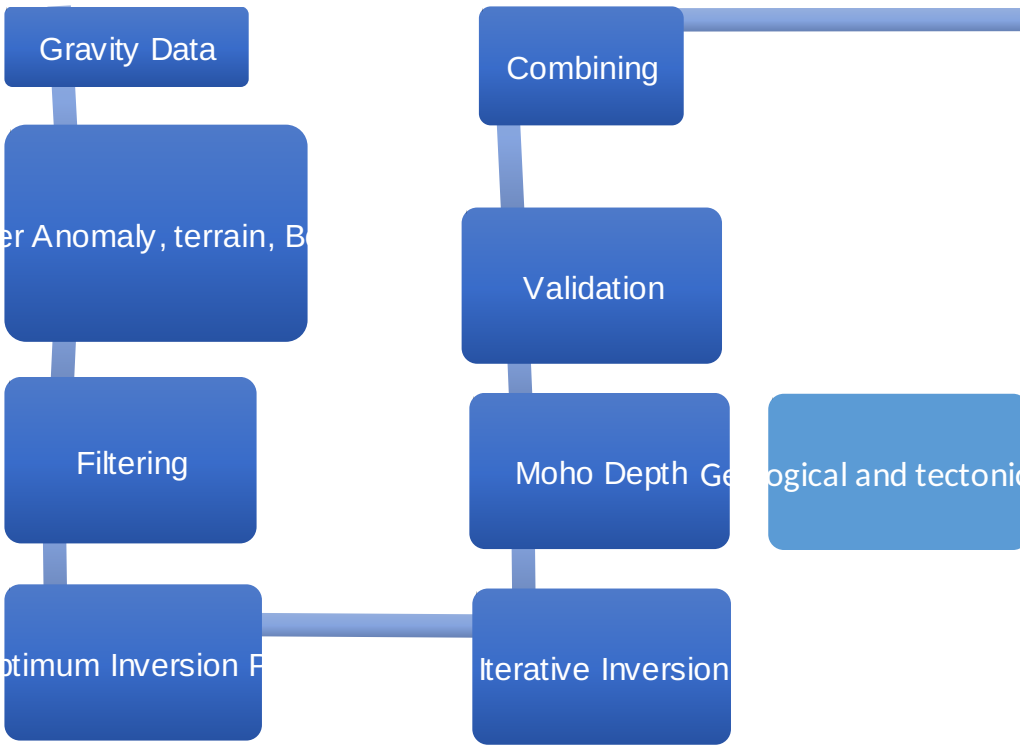


Figure 4 Research Design

4.2 Gravity Data

Gravity data used to produce the crustal thickness model of Malawi Rift was extracted from the EIGEN-6C4 global gravity model downloaded from International Centre for Global Earth models website (ICGEM).

http://icgem.gfzpotsdam.de/calcstat/874c28b64e983f01bfbba9a22451e6b5179586923280e977f47bb3

The new European Improved Gravity Model of the Earth by New Techniques (EIGEN) released in 2014 is called EIGEN-6C4 and is created from a combination of multiple data. EIGEN-6C4 is a high-resolution global gravity field model Gravity Recovery and

Climate Experiment (GRACE) and Gravity field and steady-state Ocean Circulation Explorer (GOCE) s

EIGEN-6C4 was evaluated by GOCE orbit computations, GPS-Levelling comparisons and by comparisons in the spatial domain. The Gravity Field and Steady-State Ocean Circulation Explorer(GOCE) is a combination of SGG (Satellite Gravity Gradiometry) and SST (Satellite-to-Satellite Tracking) mission measuring Earth's gravity field and model the geoid with extremely high accuracy and spatial resolution (Drinkwater, et al., 2007). GOCE data helps understand the gravitational impact on solid earth physics of the lithosphere and upper mantle on earth processes. The GOCE satellite was launched in March 2009 and was the first of a series of Earth Explorer satellites launched by the European Space Agency (ESA), as part of its Living Planet Programme, to gather information for understanding critical Earth system variables. GOCE satellite has the goal to map our planet's gravity field in unprecedented detail. To counteract the attenuation effect traditionally seen in gravity data and to amplify the gravity signal, GOCE is equipped with the first space borne gradiometer, thus adding unique gradient data to existing worldwide gravity models, in particular at shorter wavelengths (Wan & Ran, 2018), (Bouman, et al., 2008), (Odera & Fukuda, 2017),.

The data was downloaded from the ICGEM website at a resolution of 0.1° degree which is equivalent to 10km on the earth's surface and a height of 3002m above the ellipsoid. Between the South pole and the Equator, there are 90^0 latitudes which are also one-quarter of the Earth's circumference. The equator-to-pole distance is equivalent to the circumference divided by four which is equal to 10,000km. Changing these units with convert 1^0 to kilometers, 1^0 is equal to 111.111km. 0.1°-degree resolution is equivalent to 11.11km which is approximately 10km to the nearest ten. The height of 3002m is a compromise between resolution, precision and the computational efficiency of the processing algorithm. The forward modelling algorithm becomes slower and less precise at lower altitudes. However, the crustal and lithospheric scale tectonic structures and features are maintained in the modelling results. The data is based on the magnitude of the gradient of the potential calculated on or above the ellipsoid including the centrifugal potential (Barthelmes, 2013).

Gravity meters do not give direct measurements of gravity. Readings have to be

multiplied by instruments calibration factor to give value to the observed gravity. Raw observed gravity

The scalar gravity of the ellipsoidal reference earth (normal earth) was removed from the raw gravity data to produce the gravity disturbance. Signals anomalous to the normal earth due to terrain, sediment, and elevation remained in the gravity disturbance (Fig. 6). The Bouguer effect and terrain effect were removed from the gravity disturbance in a spherical earth approximation (e.g., Uieda and Barbosa, 2017). Etopo1 data as shown in Fig. 7 was used to calculate these effect using densities of 2670 kg/m^3 for the continental crust and -1630 kg/m^3 for the water body's. The Bouguer and terrain effects (Fig. 8) were subtracted from the gravity disturbance to produce the complete Bouguer gravity disturbance (Fig. 9). The gravity effect due to sedimentary basins was also removed from the Bouguer gravity disturbance. Sediments have a smaller density than the crustal density, which introduces an overcompensated anomaly to the data after Bouguer plate correction.

The three sediment layers of CRUST1.0 (Laske, et al., 2012), with different densities based on the depth of each layer, were used to calculate the gravity effect separately. The calculation is based on the density contrast between each layer and the earth's crust. The total gravity effect of the sediments as shown in Fig. 10 was removed from the Bouguer disturbance to produce the Bouguer disturbance corrected for sediments as shown in Fig. 11. The gravity correction procedure assumes that all the signals from the earth crust and the mantle are removed or negligible, such that the only remaining signal is from the anomalous Moho (Uieda and Barbosa, 2017). The corrected gravity data were used as input in the inversion process.

Gravity measured at the physical surface of the earth must be distinguished from normal gravity (ellipsoid surface). Determination of the geoid, extrapolation and interpolation of gravity and investigation of the earth's crust are products of gravity reduction (Heath, 2017). The gravity field at the earth's surface is stronger at the poles than at the equator due to its slightly irregular oblate ellipsoid. The distribution of density is also uneven mostly in rigid crust causing gravity variations from expected value as the measurement positions change. Identifying the causes of these anomalies is vital so that they can be corrected while using the gravity technique to explore the subsurface.

Gravity observations can be used to interpret changes in mass below different regions of the Earth. Th

Gravity requires many corrections to adjust the observed value of gravity to an absolute value and to take the effects of topography, terrain, elevation, motion, and other factors into account. The largest contribution to the model is the gravity reference field which is a mathematical model of the earth's worldwide gravity called the theoretical gravity or latitude correction. A sequence of gravity corrections is applied to the original gravity reading and result in variously named gravity anomalies. The observed gravity anomaly has been corrected for Earth rotation, latitude, tidal effects, and gravity meter fluctuations.

Free-air correction accounts for the fact that the measurements were not made at sea level. It includes an assumption that except for air there is nothing between the observation point and sea level. There is a difference more than a simple change in elevation from the estimated point and where the actual point is driving to the next logical step in the process (Lowrie, 2007).

Bouguer correction accounts for gravitational attraction of the mass above sea-level datum. Due to the variation in mass between the observation points and sea level datum, there are still differences in gravity even after elevation corrections. During Bouguer correction effect of gravitational pull as a function of change in elevation by approximating the horizontal rock layer present below the observation point is eliminated.

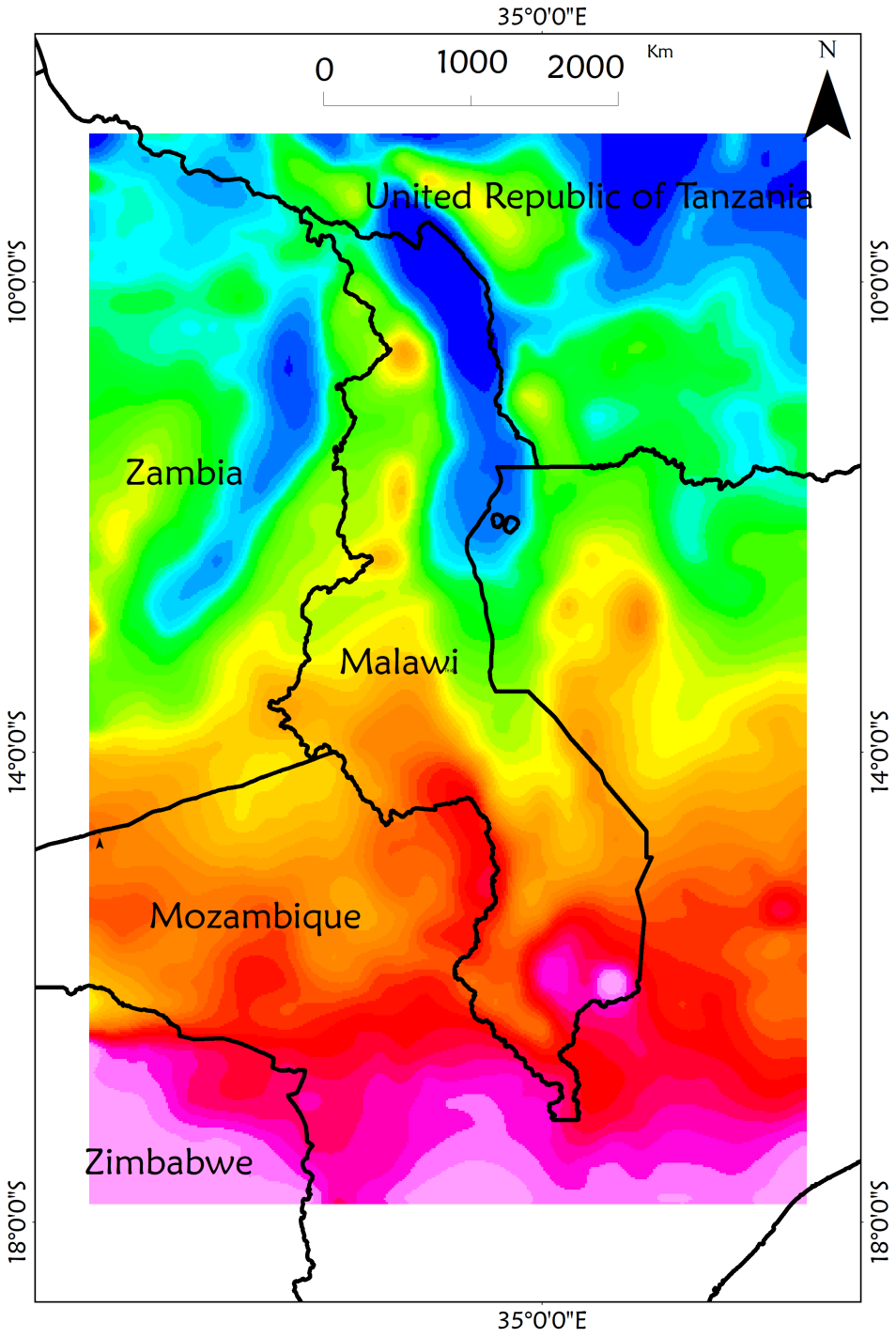
Terrain correction takes into account for undulations of topography above and below the elevation level of an observation point. While acquiring field survey, nearby topography such as hills and valleys attracts the mass in the gravimeter and reduces the observed gravity value. For the surrounding rocks, valleys are considered to have negative density. This correction does not affect the observed gravity when in a flat survey area but it does affect when the survey area has a rugged terrain.

Bouguer anomaly is the measured gravity corrected for the known or modelled gravity effects at a planetary scale. It is the discrepancy between the corrected, measured gravity and the theoretical value predicted for a datum surface. A Bouguer corrected

gravity anomaly map of the Malawi rift and its surrounding was calculated from the data downloaded fr

The gravity map was made using numerous gravity measurements along and surrounding the Malawi Rift. Gravity measurements were processed to a sediment-free Bouguer anomaly. The data was then gridded so that the randomly spaced data are converted to a representation of the gravity field at equally spaced locations. Gravity anomaly maps are shown as colour figures with warm colours; reds and oranges showing areas of higher gravity values and cool colours; blues and greens showing lower values. The gravity anomaly map contains information about rock density, depth and distribution of anomaly source rocks. Maps can be derived from the original gravity anomaly grid by using mathematical tools to enhance parts of the gravity field.

a. Raw Gravity


35°0'0"E
0
1000
2000
Km
N
United Republic of Tanzania
Zambia
Malawi
Mozambique
Zimbabwe
10°0'0"S
14°0'0"S
18°0'0"S
35°0'0"E

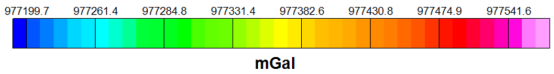
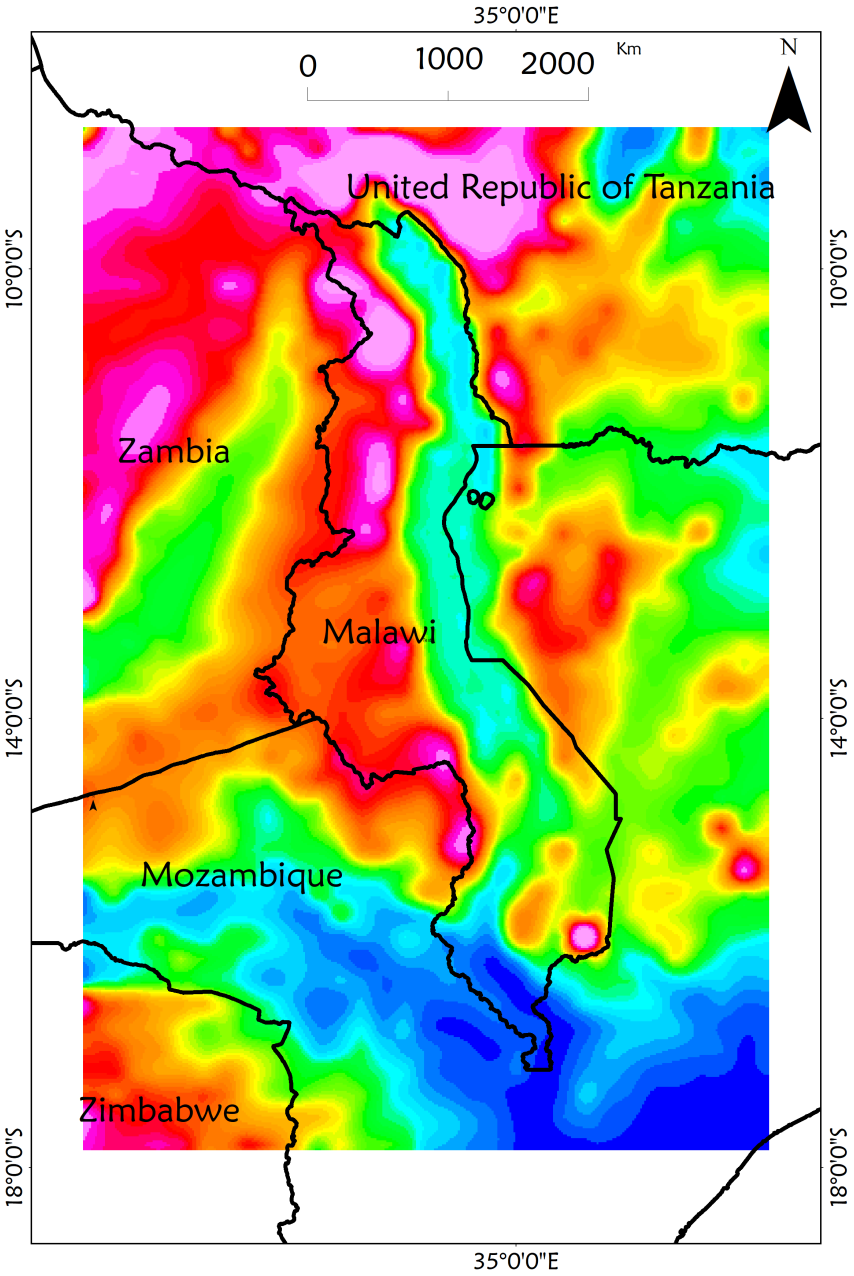


Figure 5 Raw Gravity

b. Etopo1 Map



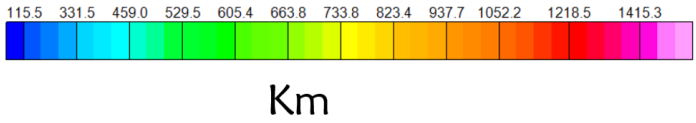
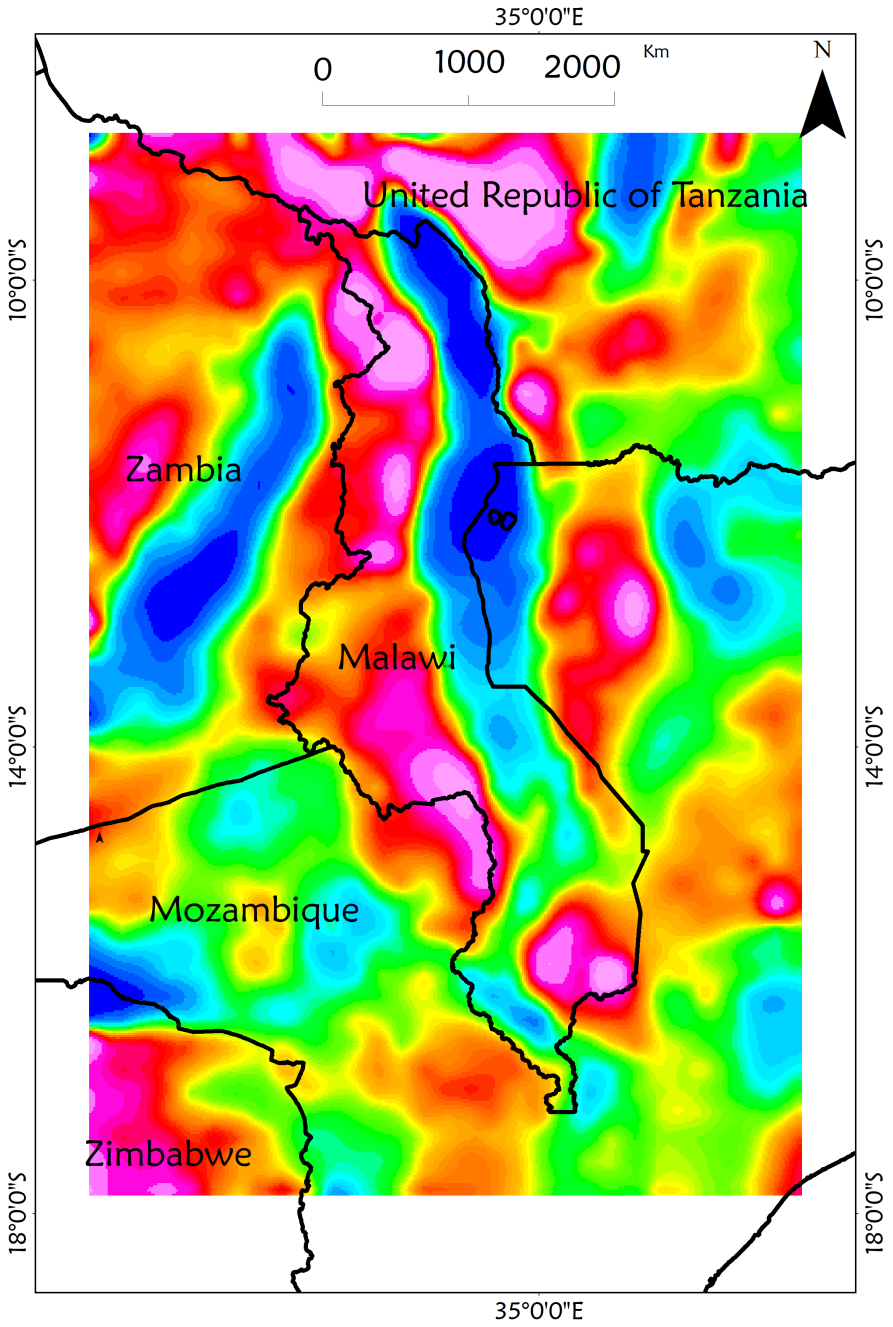


Figure 6 Topography

c. Gravity Disturbance Map


35°0'0"E
0
1000
2000
Km
N
United Republic of Tanzania
Zambia
Malawi
Mozambique
Zimbabwe
10°0'0"S
14°0'0"S
18°0'0"S
35°0'0"E

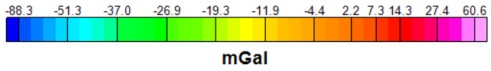
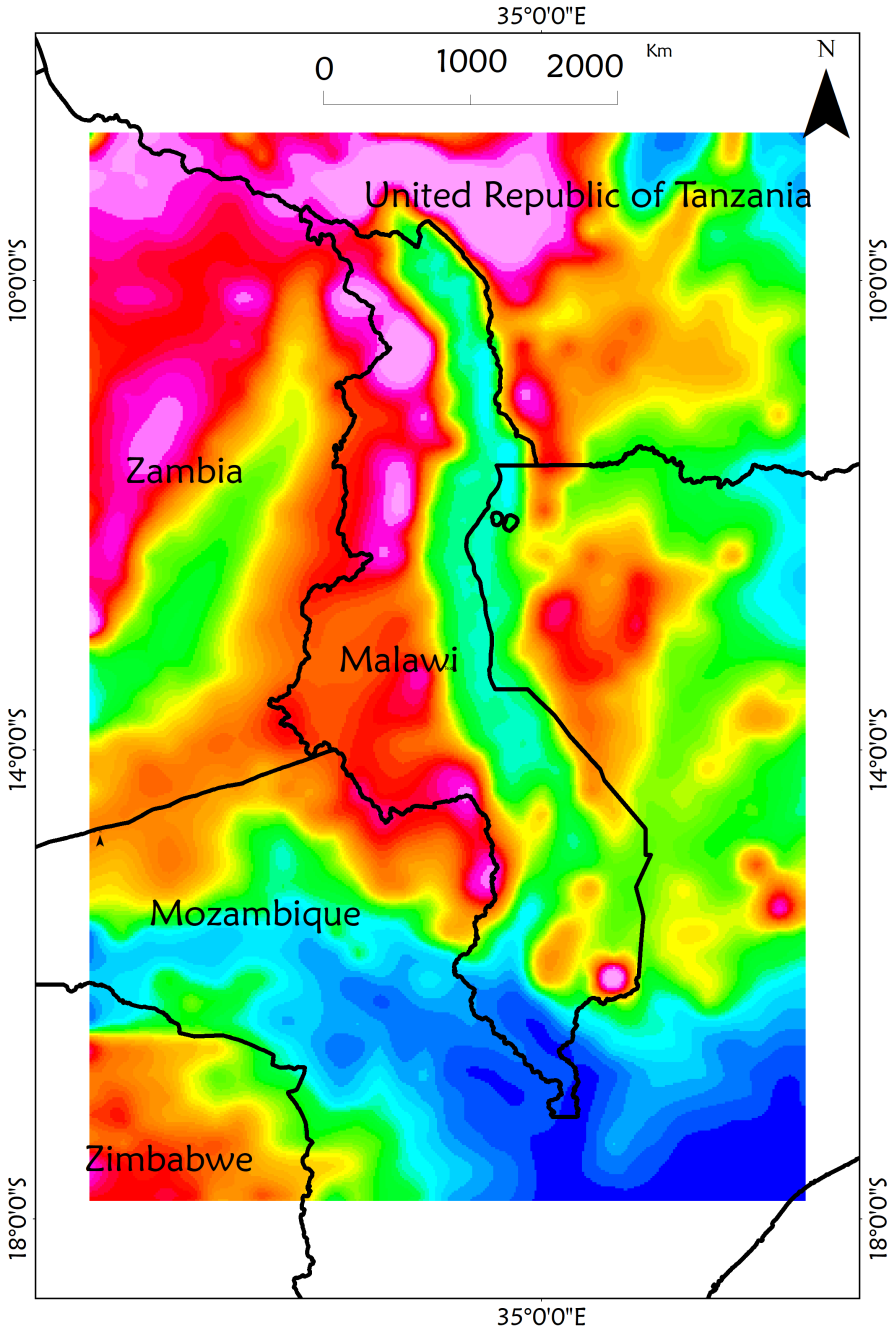


Figure 7 Gravity Disturbance Map

d. Topography Effect Map



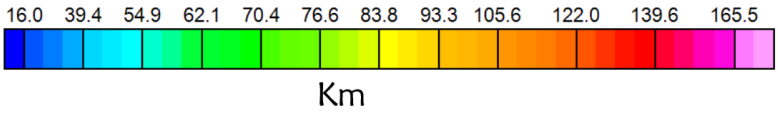
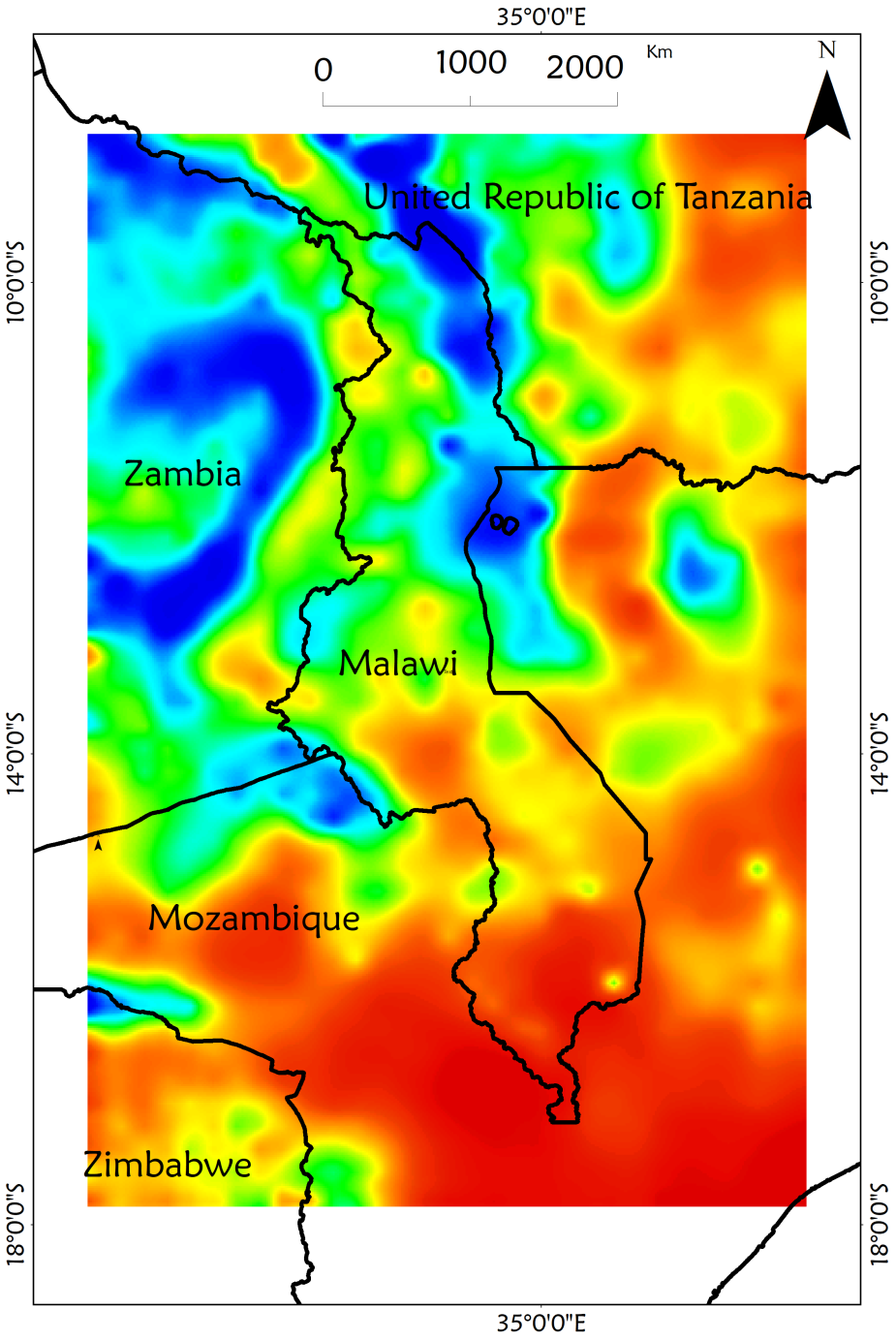


Figure 8 Topography Effect Map

e. Complete Bouguer Disturbance


35°0'0"E
0
1000
2000
Km
N
United Republic of Tanzania
Zambia
Malawi
Mozambique
Zimbabwe
10°0'0"S
14°0'0"S
18°0'0"S
35°0'0"E

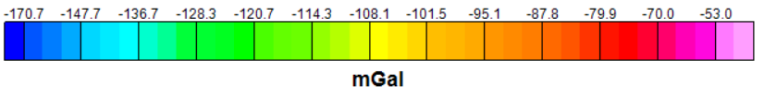
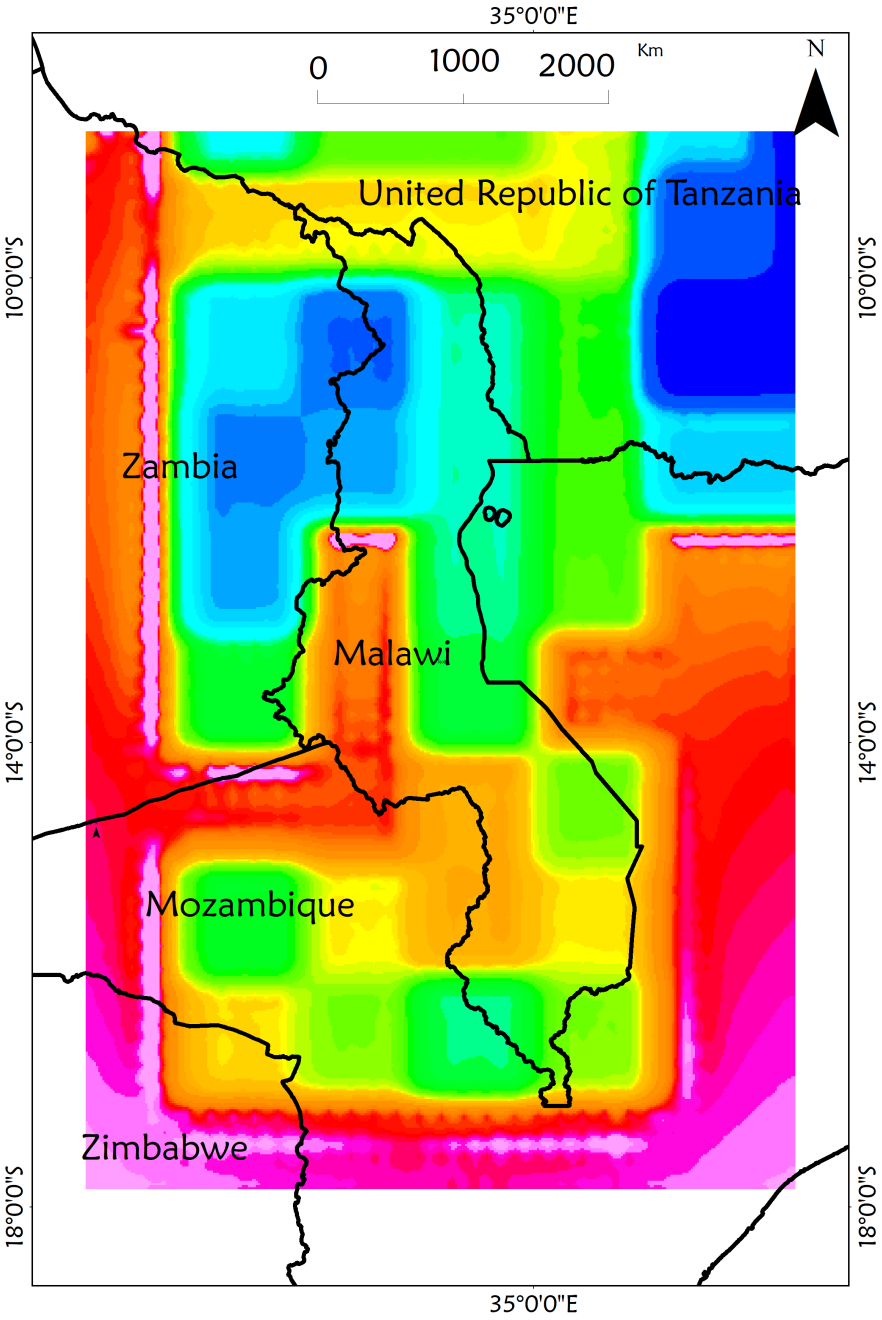


Figure 9 Complete Bouguer Disturbance

f. Total Sediments Map



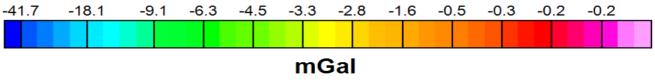
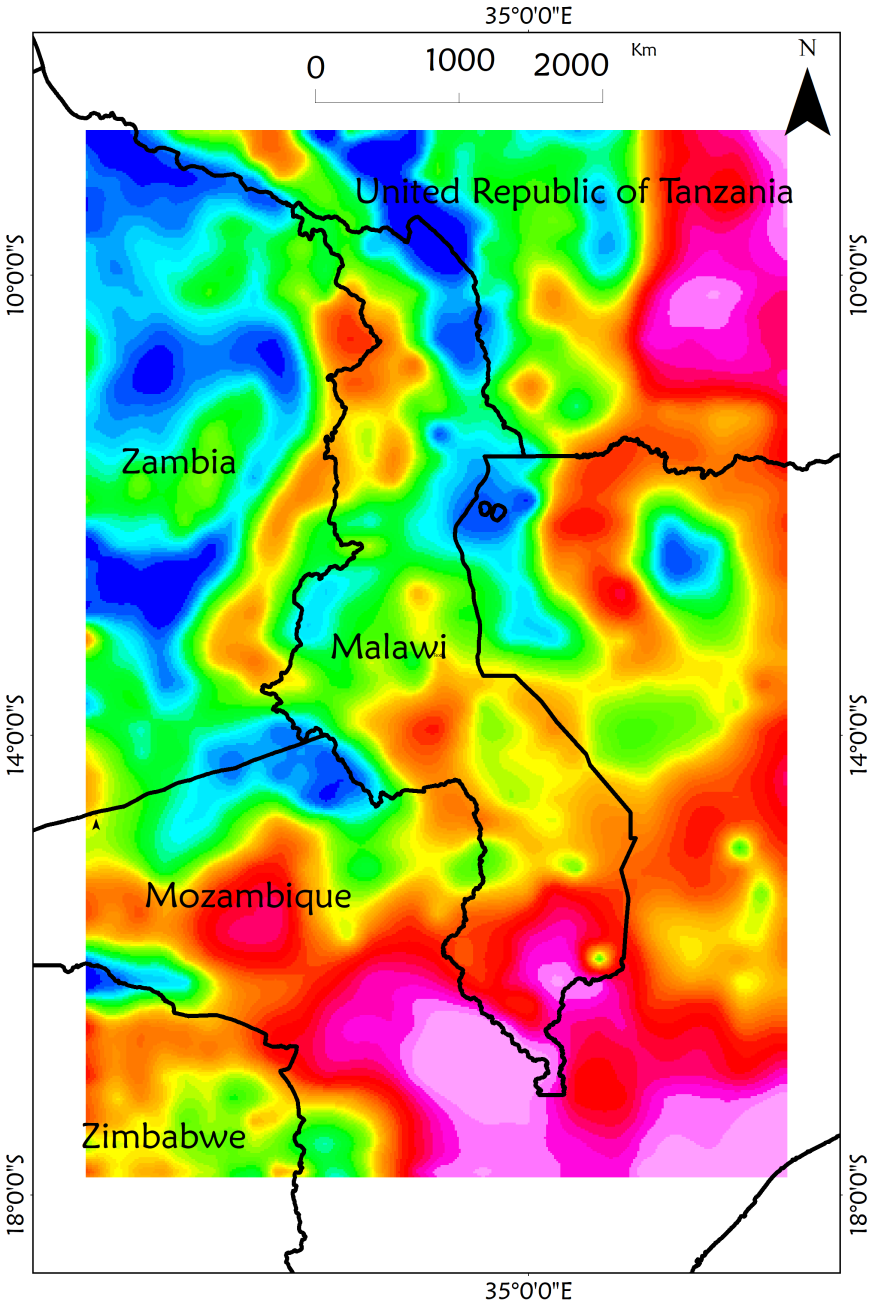


Figure 10 Total Sediments Map

g. Sediment Free Bouguer



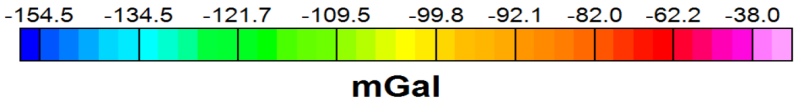


Figure 11 Sediment Free Bouguer

4.3 Seismic Constraints

Using previous articles of studies along and surrounding Malawi Rift the thickness of the crust (H) from the Rungwe Volcanic Province to the Malawi Rift was collected from different stations at different coordinates (longitude and latitude). Early studies along the rift used seismic refraction data and observations from teleseismic and regional earthquakes to examine crustal structure yielding estimates of Moho depths. Seismic data is applied in the validation of the crustal thickness model derived from gravity data. Moho depth estimates at 56 locations in the northern for receiver functions is seismic data used in this study. The seismic data collected from Borrego, et al., (2018), (Njinju, et al., 2019), Kachingwe, et al., (2015) (Table 1) and their spatial location shown in figure (8) below. The crustal thickness estimates from the dataset range from 32 and 48 km. These estimates, combined with similar results from previous studies. Taking account of these details seismic data points are applied in this study to validate the gravity derived Moho depth of the Malawi Rift produced from the research.

Table 1 Crustal Structure Results

Tectonic Region	Station Name	Latitude	Longitude	Depth
Rungwe Volcanic Province	CRTR	-9.33	33.75	47.7
	IGOM	-9.00	33.66	35.5
	MZUN	-9.15	33.52	41.2
	NKAL	-9.19	33.77	36.6
Ubendian Belt	□CHUN	-8.54	33.43	39.0
	ILIN	-9.08	33.33	42.5

	□ILOM	-9.28	33.34	41.2
	ISOK	-9.51	33.49	46.0
	ITUM	-9.40	33.19	41.2
	JILO	-8.73	33.57	40.1
	LOSI	-8.39	33.17	38.8
	MAKE	-9.26	34.10	50.8
	MATA	-8.96	33.97	42.7
	MBEYA	-9.00	33.25	43.0
	MBHS	-9.43	33.98	41.0
	UKWA	-9.45	34.22	52.2
	UNDA	-9.85	34.47	45.8
Usagwaran Belt	BAKOD	-8.84	34.80	38.2
	CHMLE	-8.83	34.03	35.4
	GAWA	-8.76	34.39	38.9
	□KIDE	-9.27	35.02	36.8
	□KIFA	-9.55	35.10	40.1
	KIPE	-9.29	34.44	44.6
	MFRI	-9.29	35.31	32.4
	TOLA	-9.59	34.58	46.0
	UWEM	-9.47	34.79	51.6
Irumide Belt	BOLE	-10.98	33.74	47.0
	CHEL	-10.59	33.81	46.3
	CPMW	-9.71	33.27	46.3
	ENUK	-11.18	33.89	45.0
	KALO	-9.91	33.64	44.5
	KAPK	-9.78	33.46	45.9
	*KAPO	-9.79	33.82	40.5
	KARM	-9.95	33.90	43.8
	LIVA	-10.61	34.11	39.4

	MLOW	-10.78	34.21	43.1
	NGON	-10.94	33.94	39.0
	SCH	-10.18	34.03	45.8
	THAN	-11.47	34.18	46.3
	THAZ	-10.83	33.59	45.9
	VWZM	-11.18	33.79	45.0
	*WENY	-10.16	33.56	51.4
Mozambique Belt	BANG	-10.11	35.65	42.2
	BUMI	-10.13	34.94	42.4
	KIMO	-10.69	36.05	38.5
	KURU	-11.20	35.46	38.9
	LIGA	-10.68	35.25	40.3
	MAND	-10.48	34.60	38.7
	MBAM	-11.25	34.79	42.7
	MKIL	-10.88	34.68	44.0
	MUDI	-9.86	34.94	51.5
	NGEAB	-10.68	35.67	38.9
	NIND	-10.14	34.58	39.4
	TIRI	-10.76	34.88	40.2
	WINOC	-9.76	35.30	45.6
	ZINI	-10.47	35.34	41.1

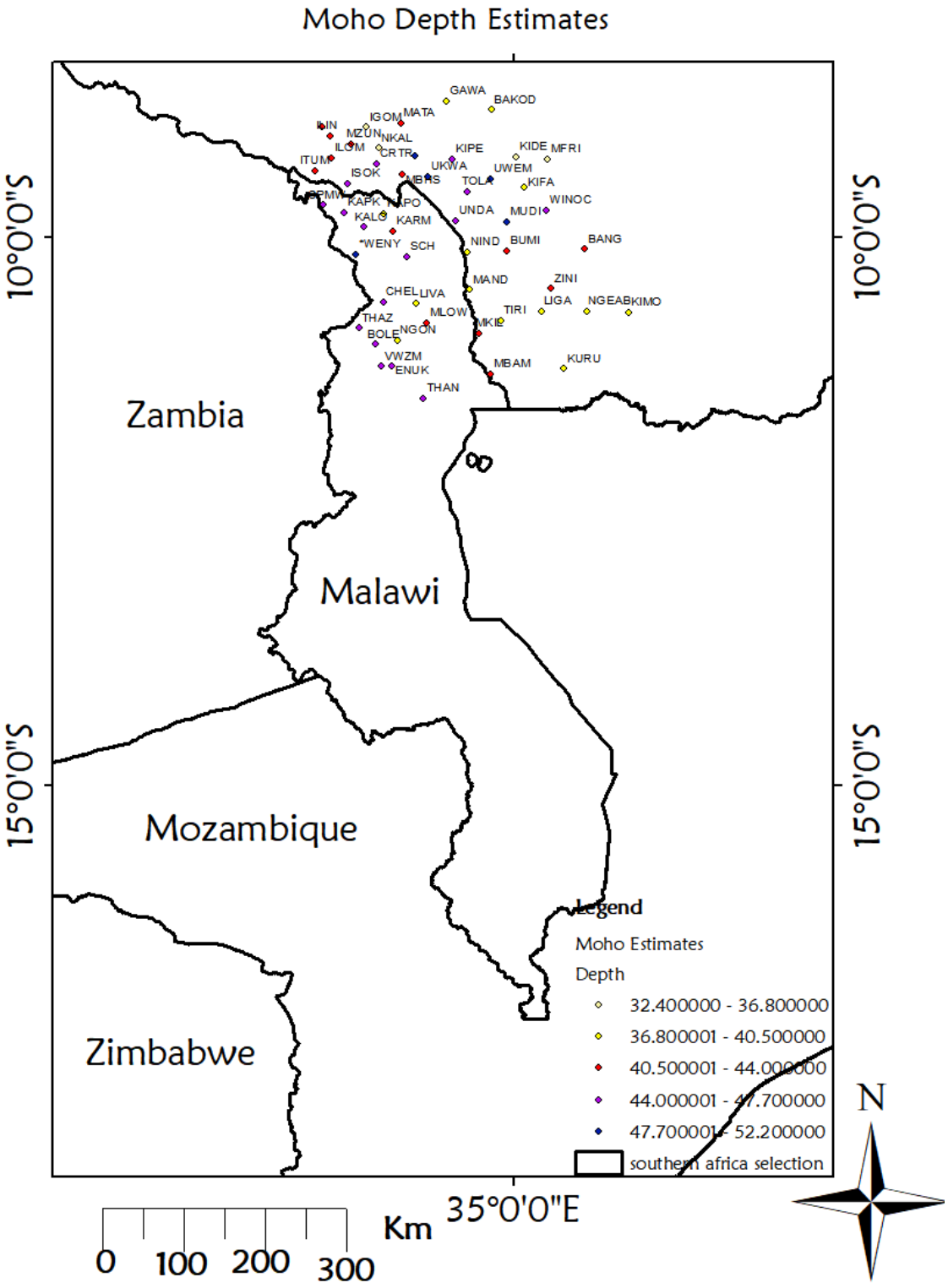

Moho Depth Estimates
GAWA
BAKOD
MATA
IGOM
IBIN
MZUN
NKAL
ILOM
CRTR
KIPE
KIDE
MFRI
ITUM
ISOK
UKWA
UWEM
MBAS
TOLA
KIFA
KPMK
KAPK
KAPO
WINOC
UNDA
MUDI
KALO
KARM
NIND
BUMI
BANG
WENY
SCH
MAND
ZINI
CHEL
LIVA
LIGA
NGEA
BKIMO
THAZ
MLOW
TIRI
BOLE
NGON
MKIE
VWZM
ENUK
MBAM
KURU
THAN
Zambia
Malawi
Mozambique
Zimbabwe
10°0'0"S
15°0'0"S
35°0'0"E
Legend
Moho Estimates
Depth
32.400000 - 36.800000
36.800001 - 40.500000
40.500001 - 44.000000
44.000001 - 47.700000
47.700001 - 52.200000
southern africa selection
N
0
100
200
300
Km

Figure 12 Moho Depth points

4.4 Inversion algorithms

The inversion of gravity data constitutes an important step in the quantitative interpretation since the construction of density contrast models markedly increases the amount of information that can be extracted from the gravity data. A principal difficulty with the inversion of gravity data is the inherent non-uniqueness that exists in any geophysical method based upon a static potential field. Since the gravity field is known only on the surface of the earth, there are infinitely many equivalent density distributions beneath the surface that will reproduce the known field (Li & Oldenburg, 1998).

This study followed a gravity inversion approach using an algorithm proposed by Uieda and Barbosa (2017) based on the Gauss-Newton formulation of Bott's equation (Chisenga & Yan, 2019). The algorithm considers the earth's curvature by using tesseroids for forwarding modelling. The forward modelling is achieved through numerically solving the Gauss-Legendre quadrature (GLQ) integration problem overcoming numerical instability by an improved adaptive discretization of the anomalous Moho (Uieda & Barbosa, 2017). GLQ integration yields accurate and efficient numerical modelling of the spherical prism's gravity potential, vector and tensor gradient components for quantitative studies of regional gravity and topography and other spherically registered mass distributions of the Earth, Moon and planets (Asgharzadeh, et al., 2006). With contrasting densities on the interface in a two-layer model, Bott's equation presents an iterative approach for estimating relief, $p(x_i)$: i = 1, 2, …, N where x_i is a set of horizontal coordinates of N-gravity observations. The approximation of pk (xi) for iteration at a kth point is given by

$P^k(X_i) = P^{k-1}(X_i) +$, i= 1, 2……....., N

Where, where G is the gravitational constant, ρ is the density contrast on the interface, is the gravity anomaly, and is the computed gravity anomaly at a point calculated from the depth model.

Uieda and Barbosa (2017) introduced a regularized method for Bott's approach that inverts gravity data in spherical coordinates in two ways.

a. the rectangular prism was replaced by spherical prisms or tesseroids.
b. they deployed a regularization parameter to control the smoothness of the inversion results while maintaining the fit between solutions and the observed data, using the Tikhonov regularization.

In this approach, the ill-posed inverse problem is transformed into a well-posed inverse matrix. Inverse problems are often ill-posed hence need to be re-formulated for numerical treatment while well-posed has a high probability of solution on a computer using stable algorithm (Kabanikhin, 2008). Inversion results from the regularized Bott's method, i.e. the Moho depth estimates, at kth iteration, are obtained by solving a parameter perturbation vector, Δp^k;

$$[A^{kT}A^k + \mu R^T R]\, \Delta P^k = A^{kT}[g^0(x_i) - g\,(x_{i,}\, pP^{k-1}) - \mu R^T R P^{k,}\ i = 1, 2, \ldots N$$

Where

A^k is a Jacobian matrix

μ is a regularization parameter

R is an L × M finite-difference matrix representing an L first-order difference between adjacent tesseroids P^k is the M-dimensional parameter vector containing M-Moho depth.

4.5 Topography Data

The crustal thickness model of the Malawi Rift is a product of the summation of topography and Moho depth. Mohorovicic discontinuity borders the earth's crust and upper mantle, and its depth is the distance between the sea level, reference geoid and the Moho discontinuity. The elevation is the distance above or below sea level and surface. Crustal thickness is the width of the crust from the earth surface to the boundary with the mantle. Etopo1-2250 built from numerous global and regional datasets was downloaded from the ICGEM website was used in this research. The Etopo1 used in this study is high-resolution data about 1.8km compared to the previous Etopo data.

4.6 Parameter Estimation

The regularized Bott's method requires a regularization parameter, a reference Moho depth, and a density contrast as parameters (Kim, 2009). Hyper parameters are parameters that influence the inversion results but are not estimated directly in the inversion. The regularized Bott's method requires a regularization parameter, a reference Moho depth, and a density contrast as parameters. These were estimated using the hold-out method. The gravity data were split into training dataset (d_inv^o) 368 points, and testing dataset (d_test^o) 1058 points, using the approach which was used to estimate the optimal regularization parameter, the reference Moho depth, and the density contrast. Testing data was used to check the quality of the chosen value for the regularization parameter while seismic constraints are used to validate the reference Moho depth and the density contrast. Parameter estimation was done in two steps:

Step one: Estimating the regularizing parameter

The regularization parameter μ controlled how smoothness is applied to the inversion result. An optimal value μ stabilized and smoothened the solution while not compromising the fit to observed data. To estimate parameters of an optimal μ L-curve criterion and cross-validation techniques are applied. This study applied the Hold-out method of cross-validation where the observed data set was split into training set d^0_{inv} and testing set d^0_{test} which are independent. The training set was used in inversion while the testing set is used to determine the quality of the chosen value μ. To obtain an estimate P^n the training set is inverted using μ_n which was the regularization parameter and is used to calculate predicted data on the same points as the testing set through forward modelling.

$$d^n_{test} = f(P^n)$$

a. The reference Moho depth, d_l, was set to 35 km and the density contrast, d_{sl}, to 750 kg/m^3, these two values do not affect the final calculated regularization parameter (Uieda and Barbosa, 2017).

b. For every $\mu_n \in [\mu_1, \mu_2 \ldots, \mu_{N\mu}]$ set on a logarithmic scale from 10^{-15} to 10^{-1}, totaling

values and using d_l and d_{sl},

i. The Moho depth at every point for each of the 32 values was estimated by inverting d_invo. The estimated Moho depth at a given point was forward modelled to produce a predicted testing data set, d_testn.

ii. The Mean Square Errors $MSE_n = \| d^0_{test} - d^n_{test} \|^2 / N_{test}$ (MSE_n =)

iii. The final regularizing parameter was 10^{-16} which corresponds to the smallest MSE_n from the 32 values indicated by the green box.

Step two: Estimating the reference Moho depth and the density contrast

The depth of the Normal Earth Moho (Z_{ref}) and the density-contrast of the anomalous Moho (ρ) are other hyperparameters of the inversion influencing the final solution although they are not estimated during the inversion. Both hyperparameters cannot be determined from the gravity data alone. Estimating Z_{ref} and ρ requires information that is independent of the gravity data, such as knowledge of the parameters (Moho depths) at certain points along and surrounding the Malawi Rift. In this study, the point estimates of the Moho depth were used to determine the optimal values of Z_{ref} and ρ. These points were collected from seismologic studies, like receiver functions, surface wave dispersion, and deep refraction experiments.

i. The regularizing parameter calculated in step one above is applied and Z_s^o, where Z_s^o is a vector N_s of the seismic crustal thickness constraints data.

ii. The reference Moho depths, Z_{ref}, varied between 33 km and 40 km with intervals of 1 km had a total of seven values.

iii. The density contrast values ρ, have five values from 350 kg/m^3 to 750kg/m^3 at an increment of 50 kg/m^3.

iv. For a total of 56 combinations of the reference Moho depth, Zref, and the density contrast, ρ;

a. The d_inv^o was inverted using each combination of Z_{ref} and ρ, and the calculated

μ, to estimate Moho depth values. Elevation data was added to the estimated Moho depth solut

b. The Mean Square Errors $MSE_n = \| Z^0_s - Z_s^{l,m} \|^2 / N_s$ for each of the 56 results were calculated.

c. The final reference Moho depth was 33.25 km and a density contrast of 750 kg/m ^{3}, which had the smallest MSE_n as indicated by the green triangle

The gravity data was inverted using the three estimated parameters and the regularized Bott's method, to produce a Moho depth model. Then topography data was also added to the Moho depth model to produce the crustal thickness model of the Malawi Rift.

CHAPTER 5

5.0 Results

5.1 Crustal Thickness Model

This study applied the approach by Chisenga & Yan, (2019) proposed by (Uieda & Barbosa, 2017), Chisenga & Yan, (2019) created a new crustal thickness model of mainland China with data derived from EIGEN-6C4 gravity data applying an approach of (Merjde, et al., 2013) using an algorithm proposed by (Uieda & Barbosa, 2017) based on the Gauss-Newton formulation of Bott's equation (João B. C. Silva, et al., 2014) and (Chisenga, et al., 2020) also derived a model of Botswana from gravity data which enlightens on the implications for the Mw 6.5 April 3, 2017, Botswana earthquake. The main objective of this project was to interpret the geodynamics of the Malawi rift by modelling the crustal thickness using data extracted from EIGEN-6C4. This section explains exhaust all the findings of the research study through crustal thickness modelling and geodynamics mapping. Therefore, the results found in the study is focused on achieving this objective.

Africa has fairly homogeneous crustal thickness with an average for the entire continent of 39 ± 2(SD) km. Although the crust on average is fairly homogeneous, there are specific areas that show deviations from the average crustal thickness. There are minimal variations between terrains of different ages and most areas do not deviate more than 5 km from the continental average. The average crustal thickness for

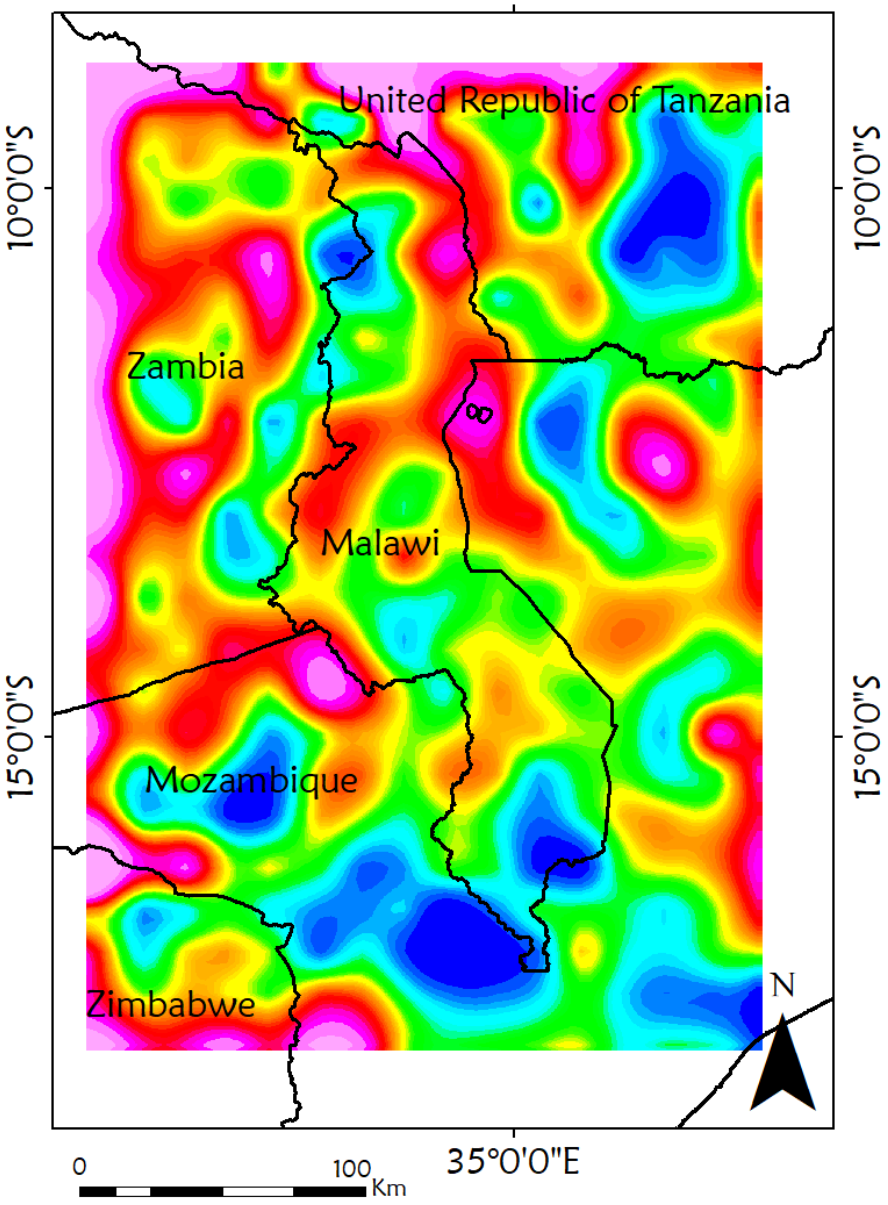
Archean, Archean crust reworked in the Proterozoic, Paleozoic and Precambrian basement covered w

The crustal thickness model of the Malawi Rift is produced by combining the validated Moho depth and topography data, section (4.6). There is a close relationship between crustal thickness and tectonic setting (Li, et al., 2006). Knowledge about the nature of Precambrian crust obtained from seismic data provides key constraints on geodynamic models of crustal genesis and evolution, and is therefore important for addressing questions about secular variation in crustal formation. The crustal thickness model, which is shown in Fig.14, was produced by adding Etopo1 map (Fig. 7) to the obtained Moho depth model. The resolved crustal thickness model shows a relatively inhomogeneous thickness estimates with a resolution of 0.1°. The 0.1° resolution reflects the highest spatial extent of the EIGEN-6C4 gravity data but the resolution of the tectonic features is □0.5° × 0.5°.

Fig. 13 gives the Moho depth estimated from inversion algorithm assuming that the gravity effects for the density contrast of the crustal thickness variations to zero at 33km altitude. The western region of Malawi has moderate to high Moho depth from the north to the central region and the depth lowers to the southern end of the country. To the eastern Malawi id dominated with lower Moho depth having only Mulanje area with higher depth. The Moho depth varies between 32km and 52 km, the depth increases abruptly to 40km to the northwest. The Moho depth obtained in this study are approximately similar to the earlier estimates determined by (Borrego, et al., 2018).

Fig. 14 shows a crustal thickness model obtained from the summation of the Moho depth estimates and the topographic data. The gravity Moho estimates in Fig. 13 augment seismic Moho estimates, fig. 12 on Malawi and surrounding areas. The crustal thickness of northeast region of Malawi is higher ranging between 38 to 40km. The crust thins out to the north east which is in the Lake Malawi. The central region is dominated by a crust thins out explaining its plain nature (Thatcher & Walter, 1968). Having areas around the Kirk range, Lilongwe-Mozambique border and Ntcheu-Mozambique border with moderate thick crust. The southern region of Malawi has a thickness range of 33 to 35km. There is a partial variation of thickness along the Malawi Rift having higher values in the North. Having an overall crustal thickness of Malawi range from 33 to 40

km.


United Republic of Tanzania
Zambia
Malawi
Mozambique
Zimbabwe
10°0'0"S
15°0'0"S
35°0'0"E
N
0
100
Km

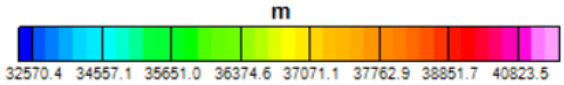
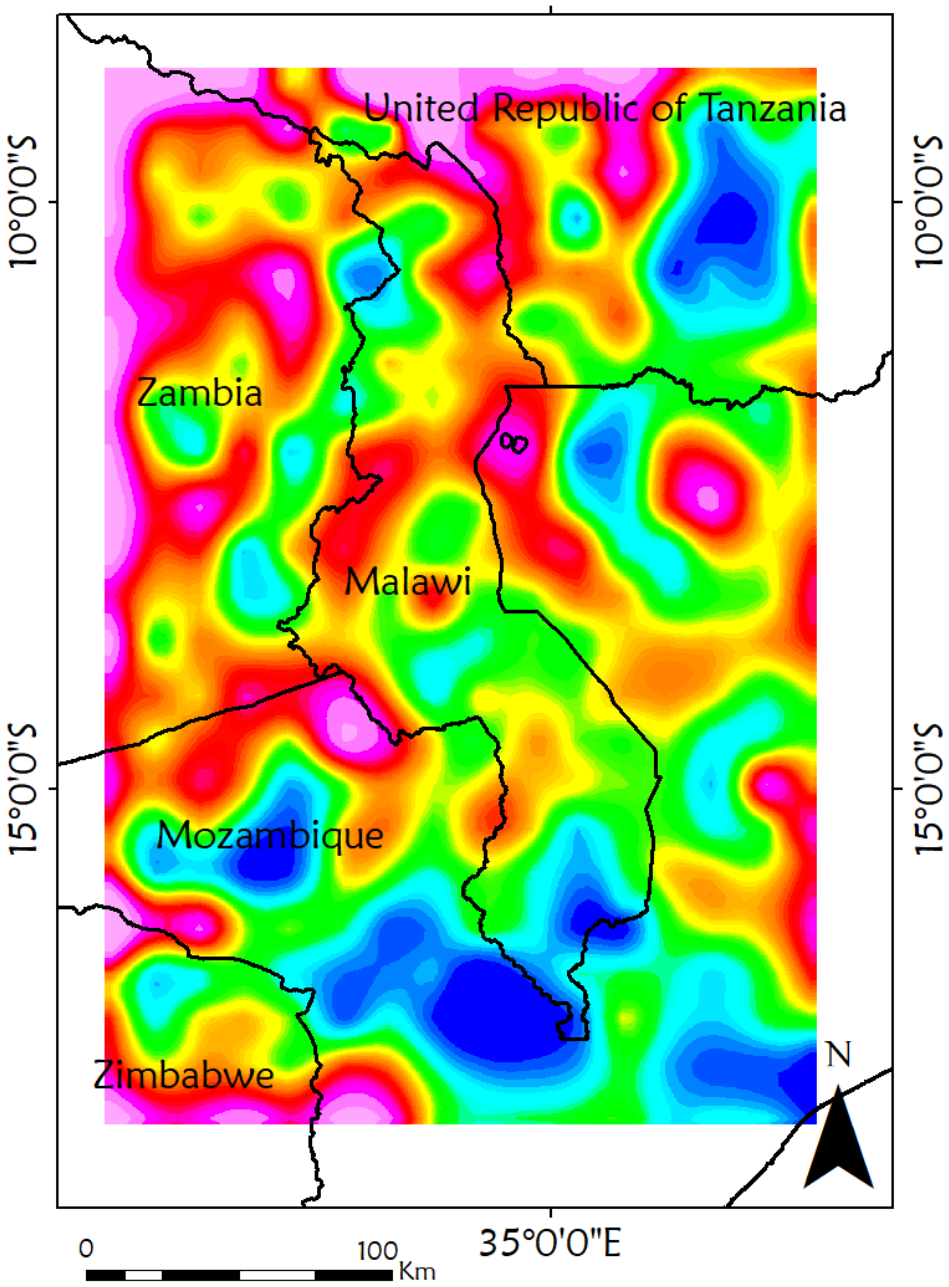


Figure 13 Moho depth Model of Malawi and surrounding areas.


United Republic of Tanzania
Zambia
Malawi
Mozambique
Zimbabwe
10°0'0"S
15°0'0"S
35°0'0"E
N
0
100
Km

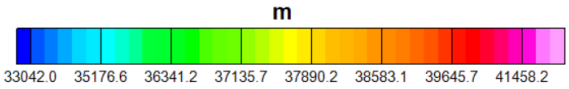


Figure 14 Crustal Thickness Model

5.2 Uncertainties due to fixed density contrast

In this section crustal thickness uncertainties caused due to the fixed density contrast and comparison of fixed density contrast with the calculated density contrast. Gravity inversion of a simple two-layer model with a fixed density contrast on the interface introduces an uncertainty in the estimated crustal thickness. This is anticipated in a continental scale study with a large lateral variation in densities for both the upper mantle and lower crust.

Global observations show that the crustal thickness varies through the tectonic regions, while the continental crust is 30 to 70 Km thick and is 2.6 to 2.7g/cm^3 dense, the oceanic crustal thickness is 6 to 12 Km and is 2.8 to 3.0g/cm^3 dense. The density contrast which is the mantle density minus crust density used varied between 0.25g/cm^3 and 0.5g/cm^3 with increase of 0.05g/cm^3 on the density contrast between the mantle and the crust which ranges from 0.28g/cm^3 and 0.48g/cm^3.

5.3 Cross Validation and Model Validation

This section gives details of the validation of Moho depth from gravity data using seismic derived Moho depth. Optimal regularization parameter (μ) was run having 33km depth as a starting estimate for all inversions and all model parameters. For this cross-validation, z_{ref} and ρ are kept fixed to 33 km and 750 kg m^{-3}, respectively. Then μ is estimated to run the validation using the seismological data of Borrego et al., (2018) to estimate zref and ρ, obtaining the final estimated Moho depth model. The sediment-free gravity disturbance was split into the training and testing data sets. The training data set is a regular grid with 0.4◦ grid spacing (twice the spacing of the original data grid) and Nlat × Nlon = 23 x 16 grid points, a total of 368 observations. The remaining 1058 points

compose the testing data set. 32 values of the regularization parameter (μ) are tested equally spaced

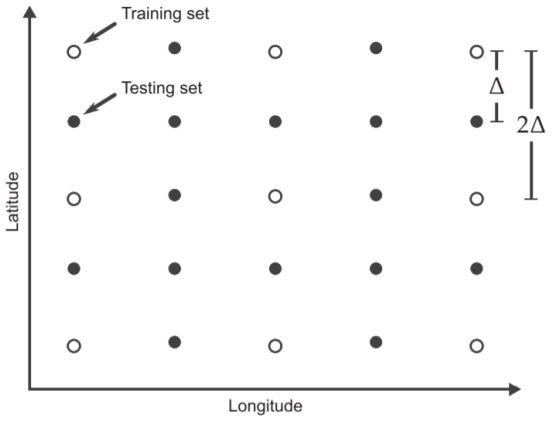


Figure 15 data splitting approach

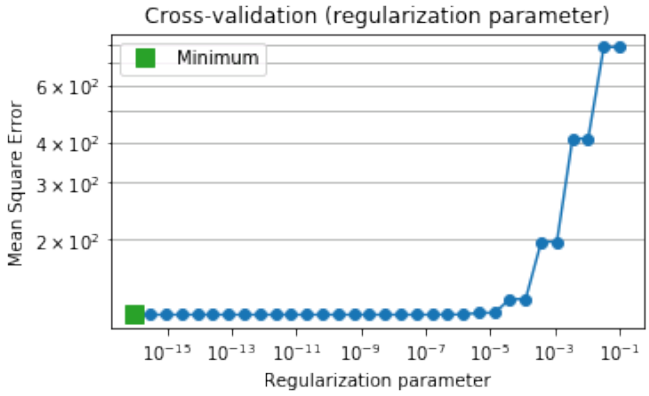


Figure 16 Estimated Regularization Parameters

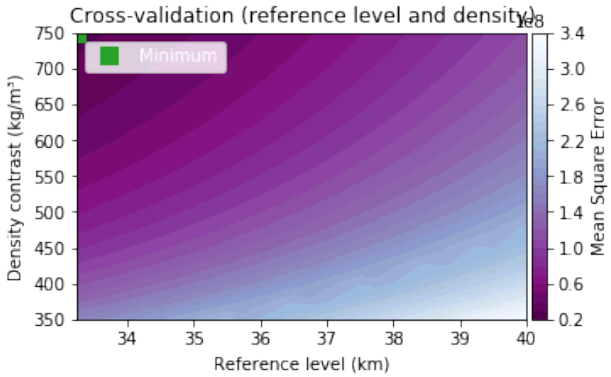


Figure 17 Estimated reference Moho depth

Example of estimating parameters using the cross-validation approach. Red rectangle representing the optimal values; Fig.15 data splitting approach in which black points represent testing data and hallow points represent training data. Where training data represents twice the original grid points and the remainder is testing data (Uieda and Barbosa, 2017); fig.16 estimated regularization parameter, fig.17 estimated reference Moho depth, and density contrast. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5.4 Geodynamics

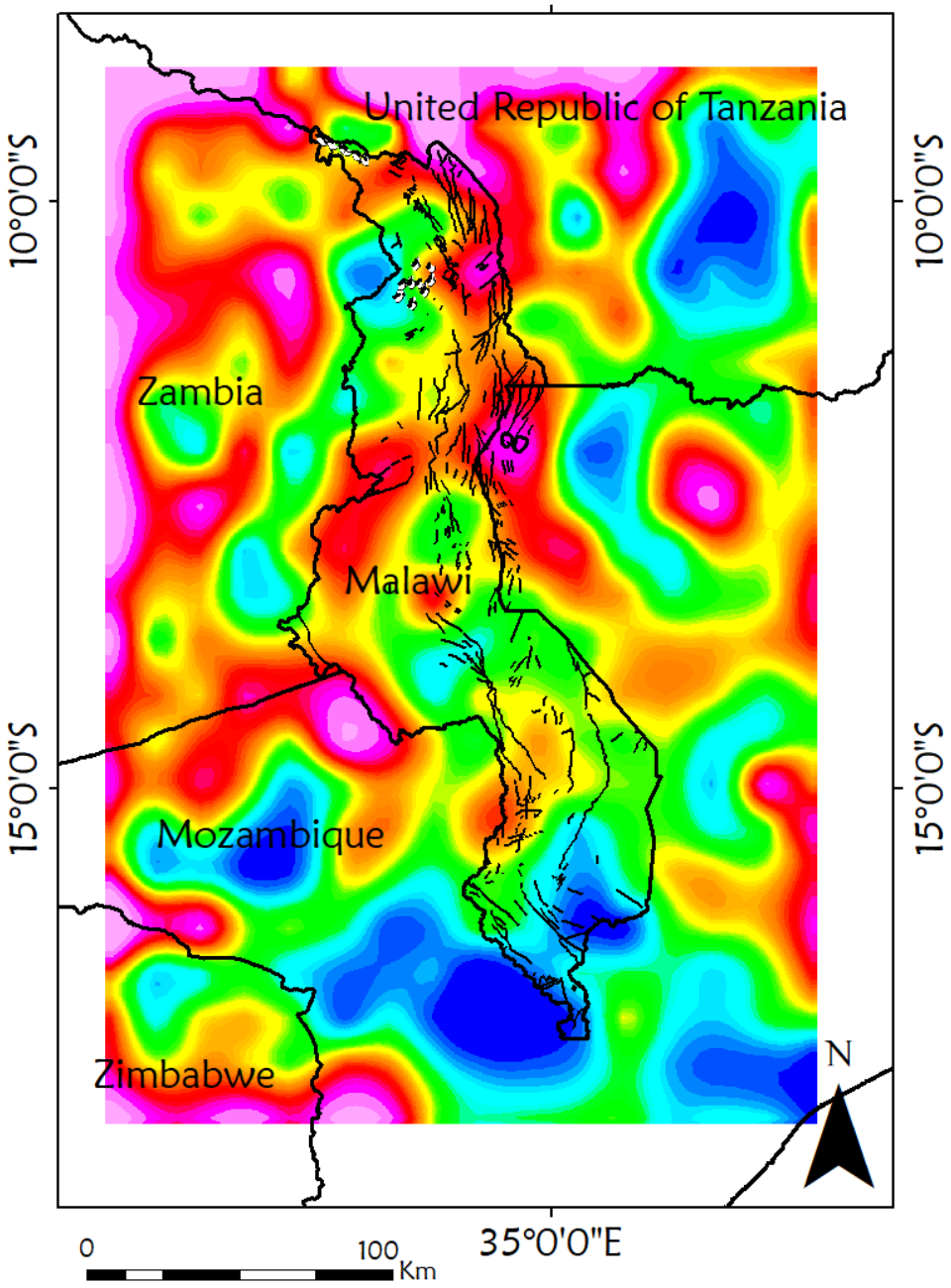
Geodynamics aims at understanding the evolution of the Earth's interior and surface over time through measuring, modelling and interpreting the configuration and motion of the crust, mantle and core of the earth and other planets (Gerya, 2012). The earth is dynamic planet although some changes are unnoticeable. The earth’s lithosphere due to different forces is broken into a number of tectonic plates which are not static hence they move relative to each other at varying speeds. When the lithosphere is subject to horizontal extensional forces it stretches, becomes thinner and eventually ruptures

leading formation of a rift valley. Rifting is governed by frictional forces exerted on the base of the litho

The EARS as an intra-continental ridge system (Chorowicz, 2005) is an active rift where the source of stress lies in the circulation of the underlying mantle (Burke, 2011). Beneath the rift the rise of a large mantle plume is doming the lithosphere upwards causing it to weaken as a result of the increase in temperature, undergo stretching and breaking by faulting (Ring, 2014). In amagmatic Malawi rift earthquake source depths are at least in part, very deep and basically span the entire thickness of the extending crust and probably also the uppermost lithospheric mantle. Ebinger et al., (2013) noted that boarder faults are long and steep and their depth extent indicate that these basins achieved their maximum length and the entire approximately 100/120 km long fault segments can rupture in single or coupled earthquakes events.

The crustal thickness and crust variations with tectonic terranes and geological data explain and interpret geodynamics. A geodynamic map of Malawi was created taking into consideration the geological and tectonic data of Malawi and the surrounding region. The crustal thickness and crustal variations explain the geodynamics and evolution of the crust. This study correlates the dynamics of the earth and crustal thickness variation. The Malawi Rift tectonic setting lies within the Nampula complex, Marrupa-Unango complex, Lurio, Ubendian belt, Irumide belt, Usagwaran belt and the Mozambique Belt.

The dynamic model of Malawi Rift is based on the delineated tectonic and geological composition and the crustal thickness model providing evidence from seismic data to help in the understanding the geodynamics of the Malawi Rift. The crustal thickness map shows evidence of geodynamic processes Malawi. The crust movements and crust reworking in relation to rifting, extension and compression are explained in relation to the crustal thickness variations.


United Republic of Tanzania
Zambia
Malawi
Mozambique
Zimbabwe
10°0'0"S
15°0'0"S
35°0'0"E
N
0
100
Km

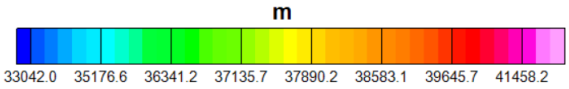


Figure 16 Geodynamic Map

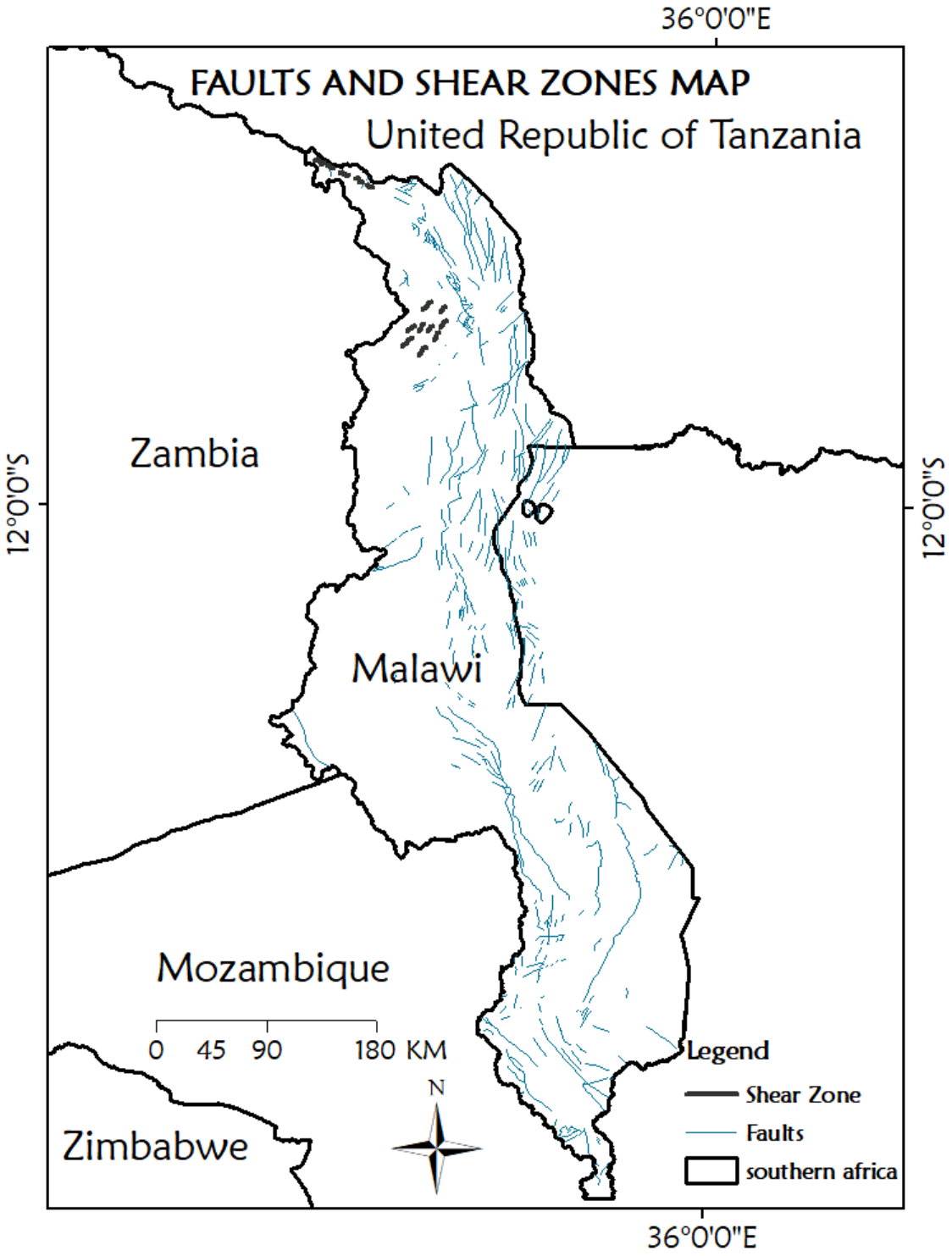

36°0'0"E
FAULTS AND SHEAR ZONES MAP
United Republic of Tanzania
Zambia
12°0'0"S
12°0'0"S
Malawi
Mozambique
0 45 90 180 KM
N
Legend
Shear Zone
Faults
southern africa
Zimbabwe
36°0'0"E

Figure 17 Faults and Shear Zones in Malawi

CHAPTER 6

6.0 Discussion

6.1. Spatial comparison

6.1.1 Moho Depth

In this section the crustal thickness of Malawi Rift in relation to previous studies is discussed. This study yielded a variation of crustal thickness ranging from 32km to 42km which is approximately closer to previous studies. These variations are from the Ubendian belt, Usagwara belt, Bangweru block, Irumide belt, Mozambique belt and Maniamba and Ruhuhu troughs. (Tugume, et al., 2012) noted that the Ubendian belt average Moho depth was 42km while (Borrego, et al., 2018) noted an average of 37.5 km. The comparison of this study's Moho depth and that of the previous of Borrego, et al., (2018) and Tugume, et al., (2012) has shown a considerable difference ranging from -1 to 12km. The Moho depth values from the new model are higher than the previous models of the study area. Due to high resolution the new model yields crustal variations within a tectonic terrane higher than the previous models.

Table 2 Moho depth and Difference

Moho depth and Difference	Lower depth (km)	Upper depth (km)
Borrego, et al., (2018)	32	48
Tugume, et al., (2012)	34	40
This study	31	52
This study - Borrego, et al., (2018)	-1.0	4
This study - Tugume, et al., (2021)	-3.0	12

6.1.2 Crustal Thickness

6.1.2.1 Eastern Region

The link to tectonic province is less clear, even though most seismic depth estimates are within ±5 km

The crustal thickness model shows a thicker crust along the northern part of the Malawi Rift. There is a moderate distribution of sediments in the Malawi Rift which is a valley occupied with water. The gravity model highlights features in the region that are more comparable to tectonic maps than the previously published crustal thickness models. The model depicts a moderate content of the sediments along the rift which is a valley. With regard to the formation of the Malawi Rift there is a minor indication of any crustal thinning beneath the rift flanks or either side of the rift.

6.1.2.2 Western Region

From the processed data the western part of Malawi has higher topography than the eastern which contains the Malawi Rift system. From tip north-west of Malawi down to the mid-south-west topography is high but it tends to decrease down into Mozambique as shown in figure (6 & 8). This is in correspondence with the variations in the lithospheric thickness inherited long after the Pan-African collision of the different lithospheric blocks.

The northern region of Malawi has low gravity, it tends to increase from the central region to the southern region into Mozambique. However, most of the rift has low gravity distribution, figure (5). The western Malawi has higher gravity disturbance than to the eastern. It gets lower to the south-west into Mozambique whilst some areas in the southern eastern gravity disturbance increased, figure (7).

Fritz et al., 2013 noted that the Malawi Rift traverses a complex array of Precambrian orogenic belts and Paleozoic-Mesozoic Karoo sedimentary basins. The most notable Karoo sedimentary basins around the Malawi Rift are the Luangwa Rift, the Ruhuhu and Maniamba troughs, and the Shire Graben. This study shows that the northern tip has moderate sediments to almost negligible down to the central. The west down to the mid-south-west is the only region in Malawi that shows a higher content of sediments; figure (10). A complete bouguer disturbance map; figure (9) shows lower values at the north but increases from the central end to the south into Mozambique. From the sedimentary free bouguer map; figure (11) it shows that it is low most of the northern to the mid

central regions having a section in the mid-eastern-north with an average and high from central, south

6.2 Implication of the crustal thickness model

This section provides possible processes and crustal movements in Malawi Rift and Malawi that resulted in the tectonic evolution of Malawi based on geophysical evidence.

In Malawi both in areas with sparse seismic data coverage and in dense seismic data coverage a spatial comparison of the gravity model and others has revealed that tectonic features are well resolved and constrained in the gravity derived crustal thickness model. The crustal thickness map shown in Fig (13), illustrates a number of features identified by the gravity model, labeled 12 to 14, in specific regions as shown by the colored polygons.

Crustal thickness is an important factor affecting structure and deep geodynamics. The thinner crust is warmer than the thicker crust by virtue of enhanced thermal conductivity of the mantle relative to the crust. The average crustal thickness over Malawi Rift is about 35km which is in good agreement with crustal thickness in other rift and cratons. Between Lakes Tanganyika and Malawi, focal depths tend to be intermediate. Extension and igneous activity along the rift became progressively more concentrated resulting into minor fault swarms taking over from the half graben boundary faults.

The crustal thickness model shows that in the northeast of Malawi variation distribution of crustal thickness is heavily faulted compared to the moderate to low thickness. This explains the active nature of the western branch of the EARS which comprises of Malawi Rift. This information will help to correlate the composition of the types of rocks which are the metamorphic basement complex; formed in the early Paleozoic to Precambrian, in the rift system, the tectonic processes which are divergent movements. The crustal thickness model explains the stretching of the crust. There is an inverse correlation between crustal thickness and heat flow. The correlation is observed both in active regions and on stable platforms. The inference of an anomalously thick crust beneath northeast Malawi may be due to the fact that they neglected velocity meta-sediments. There is a direct relationship between the geodynamics and the crustal thickness. As the crust becomes thicker there are a lot of faults accompanied depicting

the tectonic movements of the crust hence changing the composition of the geology. The major tector

CHAPTER 7

7.0 Conclusions and Recommendations

7.0.1 Conclusion

This concluding chapter is based on a synthesis in chapters 4 and 5. The Study was carried out along the Malawi Rift which is part of the western branch of the EARS. The study addressed the following objectives: creating a crustal thickness model, identifying the tectonic provinces along and surrounding the Malawi Rift and improving the understanding of the geodynamics of the Malawi Rift.

This study investigated the crustal thickness and represented the geodynamic evolution of the Malawi Rift using high-resolution gravimetric data, geology and crustal thickness and the regularized Bott's inversion method. This method used to make use of tesseroids, which are spherical prisms, to account for the curvature of the earth as the study encompasses a very large area, approximately 9.6 million km^2. The gravitational effect due to topography, terrain, and sediments were removed in a spherical approximation, considering the earth's curvature during calculation of the input gravity data and during gravity inversion. Nevertheless, the sediments map had a resolution of 1° compared to 0.1° for elevation and gravity data, which might have introduced uncertainties in the gravity data and hence the resolved Moho depth model. The resolved crustal thickness mirrored the features from tectonic map and inversion parameters were estimated using the available gravity data and seismic point observations in order to create realistic values based on the physical characteristics of the study area.

This study aimed at interpreting the geodynamics of the Malawi rift by modelling the crustal thickness using data high resolution gravity data extracted from EIGEN-6C4. The overall topographic surface is generally 500m higher in the west than in the east of Lake Malawi which implies that the lithosphere is thicker in the west. This corresponds to the variations in the lithospheric thickness inherited long after the Pan-African collision of the different lithospheric blocks. However, there is uncertainty in the fit between the

gravity and seismological points; indicating the influence of a fixed density contrast during inversion. T

7.0.2Recommendations

Based on the limitations of the study highlighted in the study the recognition that advanced geophysical analyses and advanced geospatial techniques applied the study recommends the following:

1. Need for more depth estimates from seismic data that are well distributed. The crustal thickness map from this research was validated on 16 estimates from receiver functions that are only distributed along and surrounding Malawi and none from within Malawi.
2. Need to produce a 3D earth structure and seismic tomography of the subsurface to determine the interaction and extent of the tectonic provinces into the Mantle and validate the geodynamics of the crust in the research.
3. The sedimentary map of the Malawi Rift needs to be more comprehensively studied. The current sediment map of the rift which is extracted from CRUST1.0 has a highest resolution of 0.1 degree approximately 10km. The sediment correction for Bouguer anomaly used for crustal thickness modelling might not reflect the nature of the sediments in the study area.
4. Determine the age, geology and lithology of the rift.

7.0.3 Limitations of Study

Despite an attempt at a comprehensive and holistic piece of research the work was affected by limited funding, poor network and internet connection hence making it difficult to complete the data analysis in time. However, this study is a contribution to the geophysical knowledge of the Malawi Rift and the East African Rift System.

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9.0 Appendix

Appendix I: DATA COLLECTION PROCESS

Data used in this study was downloaded from ICGEM website (International Centre for Global Earth models)

ON ICGEM HOME MENU

1. Select Regular grids under calculation service.

GRAVITY DATA

2. Under model selection select longtime model and click on ELGEN-6C4
3. On functional selection click on gravity_ell which
   The magnitude of the gradient of the potential calculated on or above ellipsoid including the centrifugal potential (eqs. 7 and 121 – 124 of STRO 9/02)
4. Low pass filtering by (gently) truncating the model.
   Start gentle cut 2190, maximum degree 2190.
5. Under grid selection drag and zoom in to select the area of interest in this case Malawi.
   Grid step [^{0}] = 0.1

-8.44

32.34 30.14

-17.75

Height over Ellipsoid (m) = 3002

6. Gaussian filter (more details)

   . None

   Filter length 0.1 ^{0}Degree

   Tide system are model's system

   Zero-degree term

   Reference system WGS 84

7. Start calculation
8. After calculation then download grid which is the gdf file used in python code for Malawi gravity data

TOPOGRAPHY

1. Under model selection click topography and select etopo 1-2250
2. Function selection click topography grid which is not a functional of the gravity field. Some functionals are calculated on the Earth's surface
   - Height anomaly
   - Gravity disturbance
   - Gravity anomaly
   - Gravity earth

During this calculation, to calculate the exact coordinates, the topography of the earth is calculated by bi-linear interpolation of the (1' x 1') grid of ETOPO 1

3. Low-pass filtering by (gently) truncating the model

   Start gentle cut: 2250

   Maximum degree: 2250
4. Under grid selection drag and zoom in to select the area of interest in this case Malawi.

   Grid step [^{0}] = 0.1

Min long -8.44

Lat 32.34 30.14 Maxi

-17.75

5. Gaussian filter (more details)

   . None

   Filter length 1.0 ^{0}Degree

   Tide system are model's system

   Zero-degree term

   Reference system WGS 84
6. Start calculation
7. After calculation then download grid which is the gdf file used in python code for Malawi topography data

SOFTWARE SETTING

Installation of the Moho-inversion

The primary files for the moho-inversion, hosted on GitHub, showed all the data (processed/unprocessed for South America)

INSTALLATION GUIDE

1. Download Anaconda application (distribution available for Windows and Unix systems)
2. Text Editor preferably (Visual Studio code) or any other(s).

Setting up procedures include:

1. Opening up the environment.yml file in conda from the moho-inversion code folder (After cloning from GitHub or if the source code is already available).
2. Building the packages from the environment in conda. An internet connection is required.
3. After building run the moho environment either in Ipython, terminal or jupyter notebook.
4. Jupyter notebook is recommended because it's easy to manage the python

code in the different cells.

5. The files to be opened in the Jupyter notebook are the moho-South-America (this is the final representation of the moho) and the sm-processed-data (this is the data entry point).
6. You can duplicate the files and make new ones bearing different names in this case, Malawi.
7. Getting Geo-data (Gravity & Topography) for Malawi using the website http://icgem.gfzpotsdam.de/calcstat/874c28b64e983f01bfbba9a22451e6b5179586923280e
8. The data in (7) above can be served into the data entry Jupyter notebook file mentioned above.