EARTH SCIENCES
RESEARCH JOURNAL
Earth Sci. Res. J. Vol. 27, No. 3 (September, 2023): 227 - 237

UNIVERSIDAD NACIONAL DE COLOMBIA

GEOPHYSICS

Crustal and tectonic structure of Northern Mozambique inferred by 2D gravity modeling

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ABSTRACT

The northern region of Mozambique has a complex geological history, with an evolution that spans from the Precambrian Era to the Phanerozoic Era. In this work, we have integrated gravity and geothermal data to delineate the geotectonic evolution of the region, by estimating the thickness of the crust and the lithosphere through which was essential to generate a representative crustal model. It was necessary to complement the knowledge of structural geometry and tectonic evolution of the region. The data used in this study are the Bouguer and geoid anomalies, topography data, and radiogenic heat. These data were pre-processed, topography and geoid anomaly data were filtered by low-pass filter in the frequency and harmonic domains to remove undesirable effects associated with the sources. The data were used to estimate the thickness of the crust and lithosphere, as well as to determine the mean density distribution within the mantle. This was achieved by using a one-dimensional approach, considering the principle of local isostatic compensation, associated with equations governing the distribution of temperature in the crust. The Bouguer anomaly was used to generate a representative crustal 2D model of this region. The results showed that the crust is thinner in Nampula and Cabo Delgado provinces, with thickness ranging from 27 to 31 km, whereas in Niassa varies between 33 and 39 km. The analysis of lithospheric thickness indicates that the provinces of Nampula and Cabo Delgado present a thinning of the lithosphere, with values ranging from 150 to 165 km. Rather than Niassa province which exhibits a thicker lithosphere, ranging from 165 to 195 km. The obtained results underwent a comparative analysis with prior investigations, unveiling a noteworthy concurrence among these findings.

Keywords: Geoid anomaly; Thermal analysis; crustal and lithospheric structure; gravity modeling.

Estructura crustal y tectónica del norte de Mozambique inferida por modelado de gravedad en 2D

RESUMEN

La región norte de Mozambique tiene una historia geológica compleja, con una evolución que se extiende desde la Era Precámbrica hasta la Era Fanerozoica. En este trabajo hemos integrado datos de gravedad y geotermia para delinear la evolución geotectónica de la región, estimando el grosor de la corteza y la litosfera a través de la cual era esencial generar un modelo crustal representativo. Era necesario complementar el conocimiento de la geometría estructural y la evolución tectónica de la región. Los datos utilizados en este estudio son las anomalías de Bouguer y geoides, datos topográficos y calor radiogénico. Estos datos fueron pre-procesados, los datos de topografía y anomalía geoide fueron filtrados por filtro de paso bajo en la frecuencia y los dominios armónicos para eliminar efectos indeseables asociados con las fuentes. Los datos se utilizaron para estimar el espesor de la corteza y la litosfera, así como para determinar la distribución de densidad media dentro del manto. Esto se logró utilizando un enfoque unidimensional, considerando el principio de compensación isostática local, asociado con ecuaciones que rigen la distribución de la temperatura en la corteza. La anomalía de Bouguer se utilizó para generar un modelo 2D crustal representativo de esta región. Los resultados mostraron que la corteza es más delgada en las provincias de Nampula y Cabo Delgado, con un espesor que oscila entre 27 y 31 km, Considerando que en Niassa varía entre 33 y 39 km. El análisis del espesor litosférico indica que las provincias de Nampula y Cabo Delgado presentan un adelgazamiento de la litosfera, con valores que van desde 150 a 165 km. En lugar de la provincia de Niassa, que exhibe una litosfera más gruesa, que van desde 165 a 195 km. Los resultados obtenidos se sometieron a un análisis comparativo con investigaciones anteriores, revelando una notable concurrencia entre estos hallazgos.

Palabras clave: Anomalía geoide, Análisis térmico, estructura crustal y litosférica, modelado de gravedad.

Record
Manuscript received: 20/02/2022
Accepted for publication: 07/09/2023

How to cite this item:
Das Flores, O. H. D. J., Dutra, A. C., Lucas, M., Abdulgani, I., & Amisse, C. (2023). Crustal and tectonic structure of Northern Mozambique inferred by 2D gravity modeling. *Earth Sciences Research Journal, 27*(3), 227-237. https://doi.org/10.15446/esrj.v27n3.101149

ISSN 1794-6190 e-ISSN 2339-3459
https://doi.org/10.15446/esrj.v27n3.101149

1. Introduction

The northern region of Mozambique has a complex geological history, with an evolution that ranges from the Pre-Cambrian to the Phanerozoic era (Bicca, 2017). There is limited literature on the tectonic history, structural/geophysical characterization, shallowness and depth of the region because of a lack of data which can be used to obtain subsurface information. Investigating geological structures of a complex tectonic area, with many superimposed evolution stages, is a difficult task and, often, the usual geological tools are insufficient.

This work aimed to investigate the crustal and lithospheric structure of northern Mozambique along three north-south oriented and one west-east oriented profiles by combining gravity anomaly, geoid anomaly, topography data and thermal analyses, to have a better understanding of the lithospheric tectonic configuration. The study area is located within the northern region of Mozambique covering the provinces of Niassa, Cabo Delgado and Nampula (Fig. 1).

To reach the objectives, first was applied geophysical techniques that allows to map the crustal thickness (crustal-mantle interface) and LAB (Lithosphere-Asthenosphere Boundary) over the entire study area and the results obtained were compared with previous studies available in the region. Then, the results of the first phase were used as a priori information in the 2D modeling that allowed to obtain the geometric configuration of the crust along the aforementioned profiles. Although there are some previous works carried out in this region (Watts, 2001, 2018; Matsinhe et al., 2021; Tessema and Antoine, 2004; Leinweber and Jokat, 2011), and other works within the lithospheric mantle structure and its geodynamic implications (e.g. Maia et al., 1990; Nyblade et al., 1992; He et al., 2021; Domingues et al., 2013; Magaia, 2009).

Although, geophysical and geologic work was done in this region (and in Mozambique in general), such as, Watts (2001) which has quantified the contribuition of rifting, sediment loading and magmatic underplating to the edge effect anomaly in the Mozambiqe Margin and their suggest that the thinned transitional crust that underlies much of the coastal the Mozambique margin is probably of oceanic rather than continental origin; Matsinhe et al. (2021) presents a density model along two profiles inferred from seismic data, suggesting that the crust consists of diluted and intruded continental crust rather than oceanic crust; Tessema and Antoine (2004) used gravity data to generate 3D models of East Africa and infer tectonic relationships with Mozambique and Madagascar; Leinweber and Jokat (2011) Used anomalous magnetic field data to assess whether continental crust exists beneath the northern Natal Valley and Coastal Plains of Mozambique; Muhammed and Mula (2021), which has studied the crustal structure and its tectonic relationships, and other works that focus on the lithospheric structure and its geodynamic implications, e.g. Maia et al., 1990 used altimetry, isostatic response and gravity anomaly data to study the lithosphere of Mozambique Ridge and their results report that the local isostatic response of the lithosphere beneath the Mozambique Ridge suggests an environment on the ridge for its emplacement, assuming the ridge is oceanic. Nyblade et al., 1992 which developed a gravity model for the lithosphere beneath the Kenya Rift Valley, the Mozambique Belt, and the Tanzania Craton and suggests a suture signature, arising from a crustal root along the boundary between the Mozambique Belt and the Tanzanian Craton and higher density crust in the mobile belt above part of the crustal root that is associated with the gravity field. He et al., 2021; Domingues et al., 2013 refers that the lithosphere of central Mozambique was involved in key tectonic events, such as the Pan-African Orogeny of the Neoproterozoic and the break-up of Gondwana in the Jurassic. Magaia, 2009 used aeromagnetic data for geological-geophysical interpretation of the geological structures of Mozambique. König and Jokat, (2010) used magnetic data to study the Mozambique Ridge and Mozambique Basin, and their generate plate tectonic model which describes the emplacement of the Mozambique Ridge of southeast Africa as the result of Breakup of Gondwana supercontinent. There still exist some open questions that still constitute a gap for the understanding of the geodynamic processes that occur in the region, such as: (a) there is no map yet published in the literature that shows the values of the crustal and lithospheric thicknesses for the northern region and also for the whole country as well; (b) there is no model that shows the geometrical configuration of the crust for this region either.

The geophysical data, especially the gravity method, combined with a geological/structural recognition can provide information on the characterization of the arrangements, relationships and compartments of rocks in depth, and the geological structures. The results obtained from analysis of gravity data form an important basis for gravity modeling with emphasis on tectonic structures (Aydin et al., 2016; Tunini et al., 2016; Samapaio 2019; Ignjatović et al., 2014).

However, due to the geotectonic complexity, there are doubts regarding the crustal and lithospheric structure, and its evolution. In this region, especially in the northern part, where the study area is located, there are almost no works that portray deep structures, which would help to better understand the subsurface. In this sense, this study sought to use the gravity data (Bouguer anomaly), geoid anomaly and topography associated with geothermal data, such as radiogenic heat and surface heat flux, to map the crustal and lithospheric structure of Northern Mozambique and generate a representative crustal geometric model for this region.

2. Geological context

Mozambique's geology can be subdivided into the Precambrian and the Phanerozoic terrains. Precambrian is mainly represented in the north and midwest of the country and covers about two-third of it (Chaúque, 2009). Phanerozoic sediments cover the area of the great coastal plains, covering a large part of the southern region of the country (from south of the Save River) and the coastline (Chaúque, 2008). Carbonatitic and alkaline intrusions, in general, occur in the north-central region of the country, cutting rocks from the Precambrian basement (Chaúque, 2008). The Pre-Cambrian, in the northern region of Mozambique, is characterized by medium and high-grade rocks and constitutes the southern end of the Mozambique Belt, as defined by Holmes (1951).

The Mozambique Belt is part of a larger orogenic belt (East African Orogeny) that occurs along the east coast of Africa, extending from northern Mozambique to Sudan and Ethiopia. Holmes (1951) defined the Mozambique Belt as the southern end of the East African Orogeny, based on structural discontinuities between the Tanzania Craton and its eastern neighbor, and dated the Mozambican Orogeny to about 1300 Ma (Chaúque, 2008). Later it was found that this belt was also strongly affected by the Pan-African thermo-tectonic episode (Chaúque, 2008).

More recent models suggest that the Mozambique Belt formed during the Neoproterozoic collision between the so-called West and East Gondwana, followed by the closing of the Mozambican Ocean (Chaúque, 2008 apud Jamal, 2005). In northeastern Mozambique, the belt became subdivided with the later recognition of the Lúrio and Namama Belts. Recent aeromagnetic images also reveal the extension of the Ubendian Belt across Lake Niassa, occupying central areas of northern Mozambique, as well as the presence of NE-SW shear zones in northeastern Mozambique (Chaúque, 2008 apud Jamal, 2005). In the northeast region of the country, Jamal et al. (1999) established the presence of ages in the range between 1000 and 1100 Ma of granitoid rocks in the Lúrio belt. A similar age (~1110 Ma) has been recorded in granitoid gneisses in the northwest of the country, along the Manica-Chimoio road (Chaúque, 2008 apud Kröner and Cordani, 2003).

Collectively, the Pre-Cambrian basement comprises high-grade gneisses, granulites, migmatites and granitoids, as well as paragneisses (Chaúque, 2008). Precise ages, determined by Jamal (2005), by the U-Pb method on zircon crystals, demonstrated that rocks from the Meso to Neoproterozoic basement of the Mozambique Belt, in northern Mozambique, were extensively reworked between 650 and 520 Ma (Chaúque, 2008). In the western sector of northern Mozambique, low-grade metasedimentary rocks, some with diamittites, occur unconformably on the high-grade basement. These metasediments are correlated with Katanguian sequences of the Luphilian arc and are marked by a later Pan-African tectonism (Chaúque, 2008).

Phanerozoic igneous activities in northern Mozambique are marked by post-Pan-African (500-400 Ma) and Cretaceous igneous assemblages (Chaúque, 2008). Post-Pan-African assemblages include a wide variety of Cambro-Ordovician intrusive bodies of circular, phyllonian or annular shape, formed by granites, syenites, monzonites, gabbros, norites and pegmatites (Chaúque, 2008). These plutonites are distributed in the post Pan-African magmatic provinces. Some monzonitic granites have ages ranging between 360 and 490 Ma; circular intrusions and veins of potassic leucogranites with hyper-alkaline differentiates, associated with syenites are dated to around 480 Ma (Chaúque, 2008 apud Afonso et al., 1998).

In general, the northern region of Mozambique is geologically characterized by the occurrence of paragneisses with a high degree of metamorphism, amphibolites, amphibolic gneiss, quartzites, granulitic gneiss, gneissic mangerites, migmatites and plutonic rocks (Norconsult, 2007). The set of occurrences of these rocks is divided lithostratigraphically into fourteen (14) geological units, as illustrated in the figure 1 (Norconsult, 2007). The geological units of the area under study are: Recent formations; Mecuburi Group; Ocua complexes; Montepuez; Meluco; Lalamo; Nairoto; Xixane; M'Sawize; Muaquia; Nampula; Marrupa; Unango and Ponta Messuli. The exposed lithotectonic units in northeastern Mozambique were assembled, deformed, and metamorphosed during the Pan-African orogeny. The available geological, structural, and geochronological data allow for the grouping of geological complexes in northeastern Mozambique into five large genetically distinct mega-units, imbricated during the pan-African Northwest Frontier orogeny (Norconsult, 2007). The five mega-units, which are an amalgamation of the geological units of the area. For example, At the base of tectonostratigraphy, a Paleoproterozoic domain belonging to the foreland of the Pan-African orogeny, and corresponding to the Ponta Messuli Complex; A Mesoproterozoic gneiss domain constituted by felsic crust reworked and transported during the Pan-African orogeny, and corresponding to the Nampula, Unango, Marrupa, Nairoto and Meluco complexes; A predominantly Neo-proterozoic domain forming a long-transported pan-African upper nappe system, exposed in the Xixano, Lalamo, M'Sawize and Muaquia Complexes, the Monapo and Mugeba klippen, and possibly the Txitonga Group; Local Neoproterozoic cover sequences: these are the Mecuburi and Alto Benfica Groups on the Nampula Complex and the Geci Group on the Unango Complex (Norconsult, 2007); The Montepuez and Ocua Complexes, interpreted as a pan-African tectonic mixture including lithologies from mega-units 2 and 3, and forming the core of the Lúrio belt. The Lúrio belt represents an important pan-African structure that reworks mega-units 2 and 3 (Norconsult, 2007).

3. Methodology

3.1. Input geophysical data

The geophysical data used to provide representative models of crustal structure for northern Mozambique are gravity data (Bouguer anomaly), topography, and geoid anomaly, extracted from the global database. The topography data and geoid anomaly were used to estimate the crustal and lithospheric thickness, which were applied to constrain the crustal 2D gravity modeling.

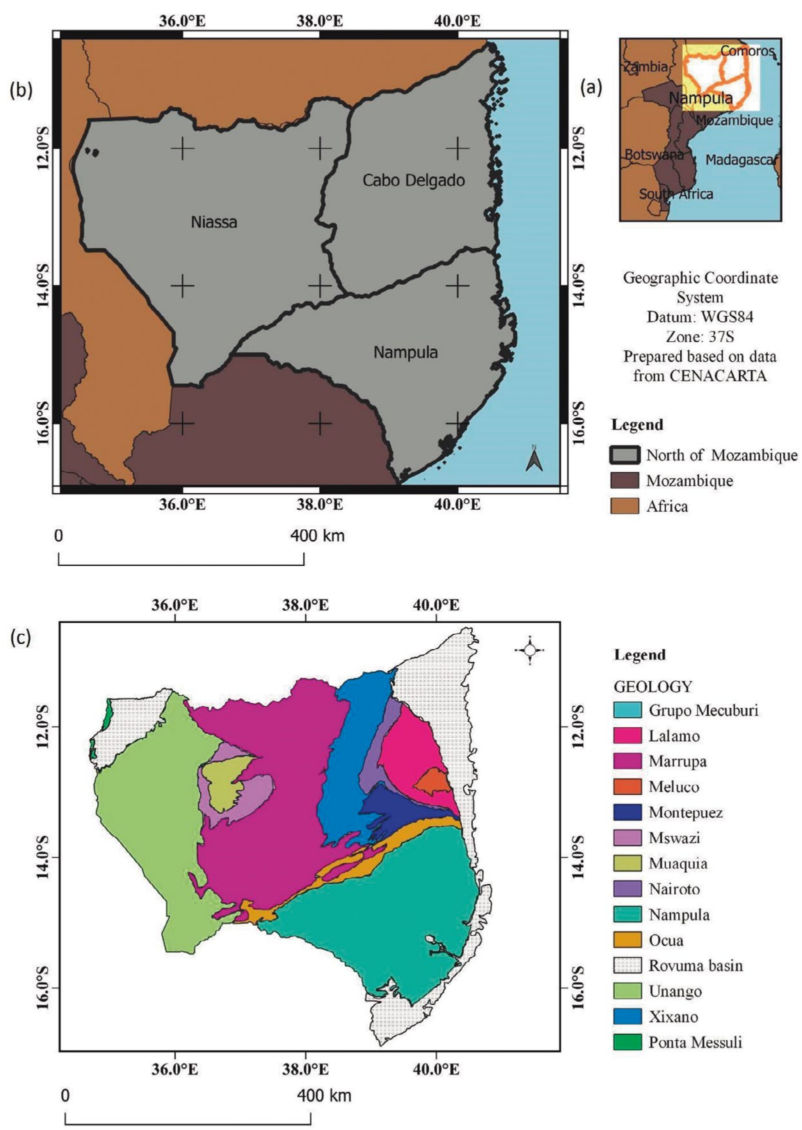

Figure 1. (a) Geographic location map of Mozambique and its respective provinces. The thin (less thick) black lines represent some countries on the African continent. (b) Map of the northern region of Mozambique and the three provinces that comprise it. (c) context and geological units of the study area.

3.1.1. Elevation data

The elevation data are from the International Center for Global Gravity Field Models (ICGEM) database. The database ICGEM used the ETOPO1 – EGM2008 (Pavlis, N.K. et al, 2012), (ICGEM: http://icgem.gfz-potsdam.de), with 1 × 1 min arc resolution, which integrates elevation and ocean bathymetry. Figure 2 shows the elevation map, where it is observed that the province of Niassa is characterized by a very high elevation, mainly in the geological units Unango and Recent Formation where the elevation varies between 600 and 200 m; and already in the units Marrupa, Muaquia and M'Sawize the elevation gives a slight drop being around 500 m. The provinces of Nampula and Cabo Delgado, which are close to the Indian Ocean, are characterized by a low elevation (100 - 500 m) when compared to the values observed in the province of Niassa.

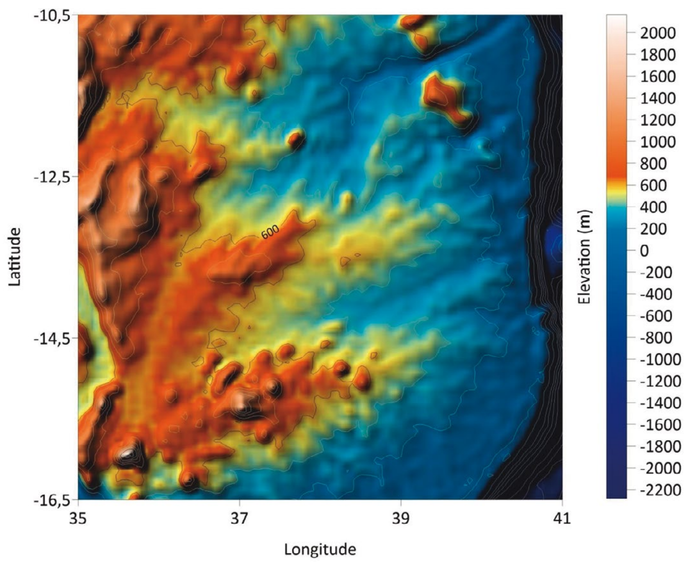

Figure 2. Elevation data extracted from ICGEM database using ETOPO1 model.

3.1.2. Geoid Anomaly

Geoid anomaly data were extracted from International Center for Global Gravity Field Models (ICGEM: http://icgem.gfz-potsdam.de) using the GECO model (Gilardoni et al., 2016), where the complete model has a spherical harmonic degree and order 2190. To retain geoidal anomalies arising from lateral density variations in the crust and upper mantle down to ~400 km depth, we apply the low-pass filter in the harmonic domain over the geoidal anomaly field we remove the first 10 harmonic coefficients (Jiménez-Munt et al., 2019). The residual geoid anomaly map with spherical harmonics coefficients up to degree and order 10 removed is displayed in figure 3. In this map it is observed that Niassa province is characterized by high and low geoidal signatures (e.g. Unango, Recent formation, Muaquia and M'Sawize tectonic units), with values ranging from -2.5 to -4.75 m. The Cabo Delgado province is mostly characterized by high geoidal signatures throughout its extension, with an average value of approximately -3.5m. For the case of Nampula Province, we observe that the geoidal signature is different in the northern and southern parts of the province, with the northern part being characterized by high anomalies (-4.75, - 4.50 m) to the detriment of the southern part which is of low anomalies (-7.25, - 6.0 m). This feature extends to the central region of the country, especially in Zambezia province.

3.1.3. Gravity data

The gravity anomalies are from a database from International Center for Global Gravity Field Models (ICGEM) and from International Gravimetric Bureau (BGI). The database ICGEM used the Earth Gravitational Model 2008 – EGM2008 (Pavlis, N.K. et al, 2012), (ICGEM: http://icgem.gfz-potsdam.de). Figure 4 shows the Bouguer gravity anomaly map of the total field, where it can be seen that Cabo Delgado and Nampula provinces are characterized by high gravity anomalies to the detriment of Niassa province. These high gravity values are associated with the fact that these two provinces are on the coast, almost in the transition zone of the continental and oceanic crust, which means that the crust in these two provinces may have low gravity signatures, with values ranging from -150.2 to -90.2 mGals. The maximum values of gravity signatures are found in Cabo Delgado province reaching approximately 59.8 mGals.

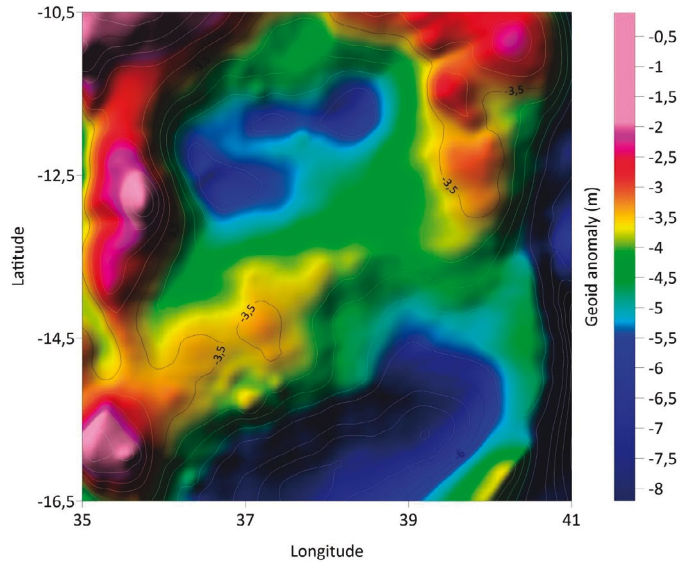

Figure 3. Geoid anomaly map, with the first spherical harmonic coefficients removed, up to degree and order 10. The geoid anomaly was extracted from the ICGEM database using the GECO model.

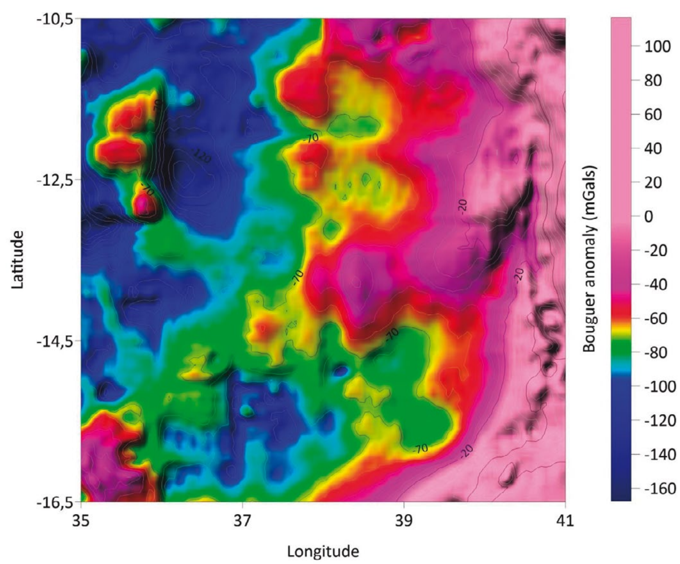

Figure 4. Bouguer anomaly map from ICGEM database, using EGM2008 model.

3.2. Spectral analysis and regional-residual separation

Spectral analysis is a tool used to separate the different spectral components existing in an observed signal, constituting a way to identify, describe and analyze signals. This process consists of transforming the data of a signal using the Fourier transform from the space domain to the frequency domain, in order to obtain the power spectrum, allowing the identification of signals corresponding to a certain wavelength and also allowing the elimination of signals referring to coherent interference sources (Spector & Grant, 1970). The analysis of the radial power spectrum allowed the determination of the range of wavenumbers suitable for separating the components at different depths.

Gravity anomalies are the superposition of anomalies (regional and residual), caused by variations in the physical properties of source bodies located in the crust. Usually, the residual anomaly is defined as the anomaly of geological interest in the region under investigation. In this case, one of the steps prior to interpreting the anomalies is the removal of the regional field to isolate the residual anomalies.

In this study, the separation of the gravity anomalies was performed using the Oasis (2000) software, and in the first phase, the Bouguer anomaly data were imported into the software, and its grid was generated by the minimum curvature method, then it was converted to grid surfer. After this conversion, the regional-residual separation was performed using a robust Beltrão et al., (1991) polynomial with a third-order surface.

3.3. Moho and LAB computation

The crust and lithosphere thickness were calculated using the Fullea et al. (2007) method. This method considers local isostatic compensation below the Lithosphere-Asthenosphere boundary and also considers a four-layer model consisting of crust, lithospheric mantle, seawater and asthenosphere.

The density distribution in the lithospheric mantle is temperature dependent and increases linearly with depth and is calculated by the equation 1:

$$\rho_m = \rho_a[1 - \alpha(T_a - T_m(z))] \quad (1)$$

Where: α is the coefficient of thermal expansion, T_α is the temperature at the depth of the lithosphere-asthenosphere boundary and $T_m(z)$ is the temperature of the lithospheric mantle as a function of depth.

The geoid anomaly is calculated from a reference level that depends on the choice of a reference column, the one that allows obtaining the best crustal and lithospheric thickness, and also considering the elevation equal to zero. The equation of local isostasy combined with thermal information used to obtain the depths of the crust and the lithosphere is described by the following Eq. (2):

$$z_L(T_a k_m - \theta) + z_L\,(z_L(T_a(k_m - 2k_c) + 2\theta) - \delta + T_a - \frac{2k_c}{\rho_a \alpha}[(\rho_a - \rho_c)z_c] + n) + + (z_c[\delta - T_a(z_c \Delta k + E k_m) - z_c\theta] - \frac{2}{\rho_a \alpha}[(z_c \Delta k + E k_m)(n + (\rho_a - \rho_c)z_c)]) = 0 \quad (2)$$

Where:

K_m and K_c are the mantle and crust thermal conductivities; p_c, p_w and p_a are the densities of crust, water, and asthenosphere (For details, Fullea et al. 2007). The parameters used in the modeling are described in Table 1.

3.4. 2D Gravity Modeling

The gravity modeling was based on the direct calculation of the gravitational field produced by a geometric shape, in which an initial model for the source body is built based on available geological and geophysical information so that the anomaly generated by this model fits the observed gravity anomaly. This process of adjusting the parameters is carried out until the calculated and observed anomalies are as similar as possible (Blakely, 1996). The modeling method used in this work is based on the Two-dimensional Modeling method developed by Talwani et al., (1959), which is one of the best known methods in geophysics where the lithological structures are drawn in the form of polygons and are represented by orthogonal profiles to the direction of the anomaly. For this, four profiles were selected, three oriented in the N-S direction and one in the W-E direction. These profiles were strategically selected in order to cover most of the structures in this region. Therefore, the initial model was constrained by the Moho thickness values, which were calculated using the method by Fullea et al. (2007) and also by geological information from the works presented in the introduction and in the geological settings. Therefore, the model consists of a set of bodies, each of which is conditioned by physical properties such as density (see Table 2), which are highlighted in the results of each profile.

Table 1. Input physical data for estimating the crustal and lithospheric thickness (Globig, et al., 2016; Telford, 1990; Fullea et al., 2007).

Parameters	Values	References
Crustal density	2780 kg/m^3	Kumar *et al.* (2013)
Water density	1030 kg/m^3	Fullea *et al.* (2007)
Asthenospheric density	3200 kg/m^3	Fullea *et al.* (2007)
Lithospheric mantle density	$3200[1 - \alpha(T_\alpha - T_m(z))]$	Fullea *et al.* (2007)
Thermal coefficient expansion	3,3 x 10^{-5} /K	Telford *et al.* (1990)
Radiogenic Heat	0,5 x10^{-6} W/m^3	Globig, *et al.* (2016)
Crustal thermal conductivity	2,5 W/mK	Globig, *et al.* (2016)
Mantle thermal conductivity	3,2 W/mK	Fullea *et al.* (2007)
Surface temperature	0^o C	Fullea *et al.* (2007)
LAB Temperature	1350^o C	Fullea *et al.* (2007)

Table 2. Parameter density used for crustal modeling and its respective reference where the values were obtained.

Lithology	Density (kg/m^3)	References
Leucognaisse	2640 – 2680	Telford *et al.* (1990)
Amphibolite	2740	Telford *et al.* (1990)
Gnaisse	2600	Telford *et al.* (1990)
Granite	2650 - 2700	Telford *et al*. (1990)
Quartz	2600 - 2620	Telford *et al.* (1990)
Rovuma Basin (Sediments)	2600	Kumar *et al.* (2020)
Migmatite	2700 - 2760	Telford *et al.* (1990)
Upper crust	2800	Kumar *et al*. (2013)
Lower crust	2900	Jiménez-Munt *et al.* (2010)
Mantle	3000 -3300	Hinze *et al*. (2013)

4. Results

To perform the regional-residual separation of the gravity data, first a radial power spectrum was developed in order to estimate the average depths of the basement. Figure 5 shows the map of the regional Bouguer anomaly, which, when analyzing the result, clearly shows an increase in the gravity signal following the NW-SE direction. These results reflect the deeper geological features/structures, with an anomaly ranging from -100 to 75 mGal, associated with low frequencies and consequently high wavelength.

Figure 6 shows the residual Bouguer anomaly map, that is, gravity anomalies associated with shallow geological structures, resulting from the subtraction of the total gravity field by the regional gravity field. In this map it is possible to observe a large variation of the signal in relation to the total Bouguer anomaly map, this is due to the attenuation of low-frequency anomalies from the mantle (deeper sources), that is, the residual anomaly highlights the shallow geological structures more, where several surface bodies were highlighted with strong gravity signal, due to the high frequencies with which these bodies are associated (shorter wavelength). The separation is aimed to remove only signs considered coming from the mantle and preserve the shallower sources correlated with the geological features of the crust.

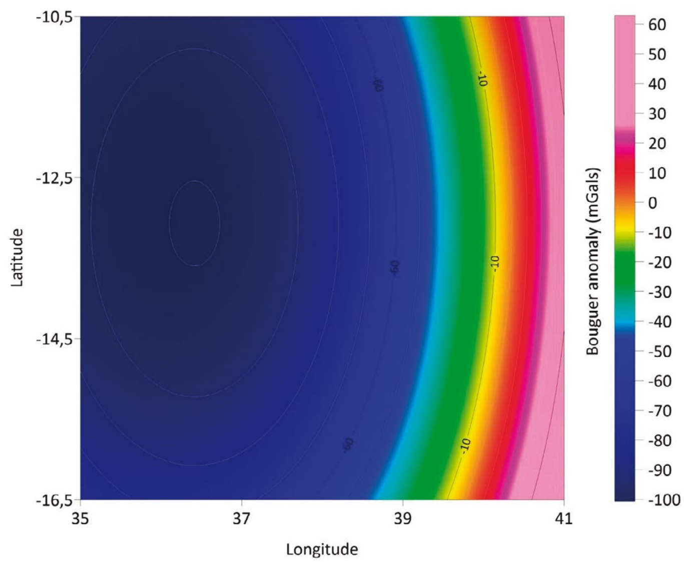

Figure 5. Regional Bouguer anomaly, obtained by third-order polynomial fit.

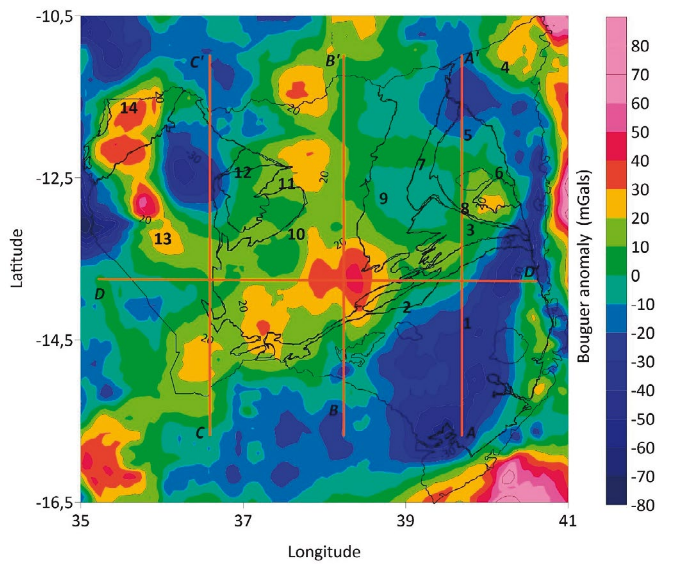

Figure 6. The Residual Bouguer anomaly, obtained by third-order polynomial fit. The orange lines denoted by A-A', B-B', C-C' and D-D' are profiles used for crust modeling. The geological units as illustrated in the figure 2 are also illustrated in this figure by black curve lines. The numbers in the maps correspond to geological units as illustrated in the figure 2, where: 1-Nampula, 2-Mecuburi, 3-Ocua, 4-Recent formation (Rovuma sedimentary basin), 5-Lalamo, 6-Meluco, 7-Nairoto, 8-Montepuez, 9-Xixano, 10-Marrupa, 11-Muaquia, 12-M'Sawize, 13-Unango, 14-Recent formation.

4.1. Moho and LAB depth

The northern region of Mozambique is made up of three provinces, and the results shown in the map in figure 7. Our findings reveal a variation in the thickness of the crust that displays a noteworthy resemblance to the elevation. In Niassa province, high values of crustal thickness (Moho depths) are observed, characterizing it as the region where the Moho reaches its maximum value. These values range from 33 to 39 km and increase in an east to west direction. The crustal thickening can be examined by considering the geological units, namely, Unango and Recent Formation, both located in the western portion of Niassa province. The provinces of Nampula and Cabo Delgado are characterized by thinner crust, and in these regions the crust varies of about 27 and 31 km, and this can reach 35 km in some parts of Cabo Delgado province, for example in the north-western part of the Rovuma Basin tectonic unit. However, the distribution of crustal thickness values throughout the area leads us to classify it into three distinct categories: (a) thicker continental crust, located in the western portion of the area, identified by a reddish rectangle; (b) intermediate crust, present in the central region, also identified by the reddish rectangle; and finally, (c) transitional crust, which constitutes the transition zone between the continent and the ocean, located in the eastern part of the area, characterized by a lower thickness and minimum values of crustal thickness. This area is also recognized as a passive margin region (see Fig. 7).

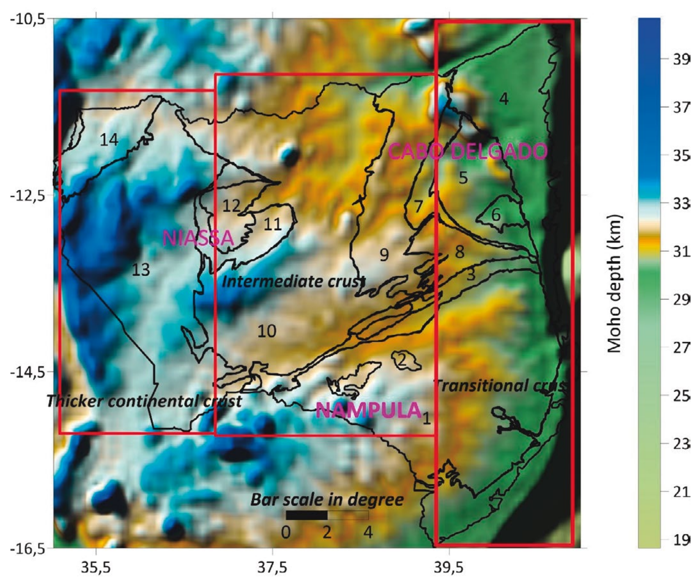

Figure 7. The map of the Moho depth. The crustal structure inferred by integration of the elevation and geoid anomaly data. Crustal structure inferred by integration of elevation and geoid anomaly data. The geological units as illustrated in the figure 1 are also illustrated in this figure by black curve lines. The numbers in the maps correspond to geological units as illustrated in figure 2, where: 1-Nampula, 2-Mecuburi, 3-Ocua, 4-Recent formation (Rovuma sedimentary basin), 5-Lalamo, 6-Meluco, 7-Nairoto, 8-Montepuez, 9-Xixano, 10-Marrupa, 11-Muaquia, 12-M'Sawize, 13-Unango, 14- Recent formation.

Figure 8 shows the results of the thickness of the lithosphere, with the regions of Nampula and Cabo Delgado provinces being characterized by a thinner lithosphere with values ranging from 150 to 165 km, while a thicker lithosphere (LAB) is observed in Niassa province, where it varies between 165 to 195.0 km in depth. As in Moho, the LAB increases in an east to west direction, this is justified by the fact that the eastern part is on the oceanic shelf side, which generally has a smaller crustal and lithospheric thickness, with a high density due to basaltic constitution or composition of basaltic rocks. Thus, in contrast to Moho's values, our lithospheric-asthenospheric discontinuity (LAB) results can be categorized into two distinct classes: (a) continental LAB, which stands out for being thicker and covers all geological units present in Niassa province, extending to Cabo Delgado and Nampula provinces, encompassing the Xixano and Mecuburi units; and (b) transitional LAB, which occurs in the transition region between the continent and the ocean, where minimum LAB values are observed (see Fig. 8).

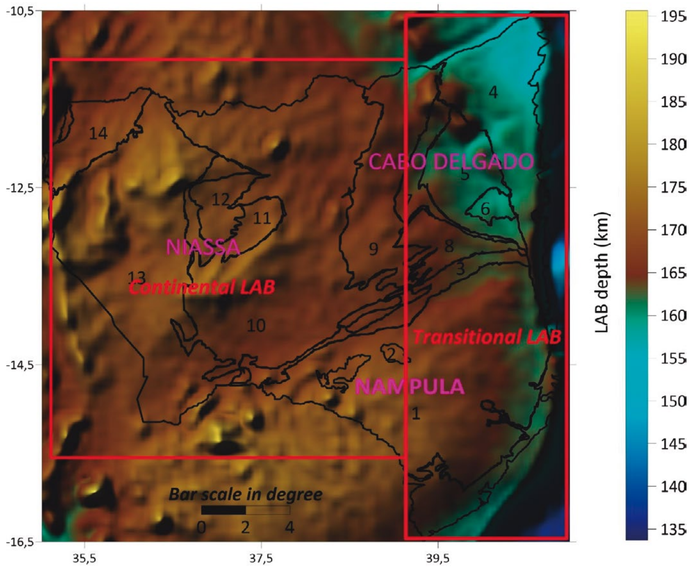

Figure 8. The map of the lithosphere-asthenosphere interface (LAB depth). Lithospheric structure inferred by integration of elevation and geoid anomaly data. The geological units as illustrated in the figure 1 are also illustrated in this figure by black curve lines. The numbers in the maps correspond to geological units as illustrated in the figure 2, where: 1-Nampula, 2-Mecuburi, 3-Ocua, 4-Recent formation (Rovuma sedimentary basin), 5-Lalamo, 6-Meluco, 7-Nairoto, 8-Montepuez, 9-Xixano, 10-Marrupa, 11-Muaquia, 12-M'Sawize, 13-Unango, 14- Recent formation.

The map in figure 9 shows the values of the mean density distribution in the lithospheric mantle. In this map, it can be seen that the lithosphere is denser along the region adjacent to the ocean shelf, covering part of Nampula and Cabo Delgado provinces, with a maximum density of approximately equal to 3250 kg/m^3, while in Niassa province the lithosphere is less dense, with values ranging from 3240 to 3250 kg/m^3.

These results give consistency to the values of the crust and lithosphere thickness found, since the regions of lesser crustal and lithospheric thickness are characterized by higher average densities in the lithospheric mantle and the regions of crustal and lithospheric thickness are characterized by lower densities, making apply the isostatic compensation principle, which is the most expected for such a region.

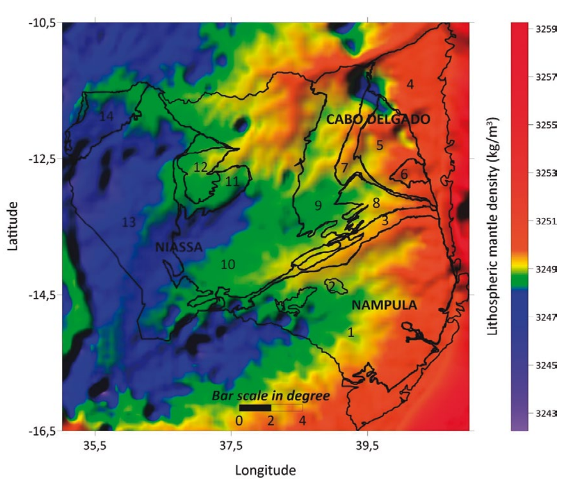

Figure 9. The map of the lithospheric mantle density, inferred by integration of elevation and geoid anomaly data. The geological units as illustrated in the figure 1 are also illustrated in this figure by black curve lines. The numbers in the maps correspond to geological units as illustrated in the figure 2, where: 1-Nampula, 2-Mecuburi, 3-Ocua, 4-Recent formation (Rovuma sedimentary basin), 5-Lalamo, 6-Meluco, 7-Nairoto, 8-Montepuez, 9-Xixano, 10-Marrupa, 11-Muaquia, 12-M'Sawize, 13-Unango, 14- Recent formation.

4.2. Gravity Direct Modeling

In the modeling of the gravity data of the present work, the Talwani et al., (1959) method from the tool available in the Oasis (2000) software called GM-SYS.

In the obtained gravity models, we tried to adjust the calculated data to the observed ones, along the geological profile created with the main lithologies. Therefore, to carry out the modeling, three representative profiles of the study area were selected, shown in figure xx, namely profile A-A', B-B', and C-C'. These profiles were also selected in a joint analysis with geological and geophysical data. Gravity anomalies were related to geological features (structures and units). Thus, for each profile, a model was generated involving the mantle and layers of the crust, and the most predominant large outcropping geological units.

The Moho results obtained in the previous topic were used as prior information and also lithological information as well as the stratigraphic column and surface distribution were also used. The referred densities were extracted from the literature and some scientific articles based on the predominant rocks in the area.

4.2.1. Profile A-A'

In figure 11, the authors present the crustal model for the A-A' profile, with density distribution in the subsurface. This model comprises the northeastern part of Cabo Delgado, where the mean values of the gravity contrast are found, and reaches the southern portion of Nampula province. According to geological-geophysical knowledge, the high values are possibly the result of greater density contrast, due to the sum of metamorphic, basic, and ultrabasic igneous rocks present in the region that can reach high densities, strongly contributing to the gravity signal, while the low ones Gravity signatures may be related to the acidic and sedimentary igneous rocks that outcrop in the Cabo Delgado and Nampula area.

In the first 9 km of depth, there is the Rovuma Basin with rocks predominantly unconsolidated sand, sandstone, claystone, limestone, and conglomerates, and along the profile, with metamorphic rocks, presenting a sharp drop in terms of gravity values, which reflects higher basement of depth values, showing as a thinner layer. The upper crust has a thickness ranging from 20 to 24 km on average, while the lower crust has an uplifted upper crust layer, its thickness varies along the modeled profile and increases from 32 in the regions below Cabo Delgado province to 37 km in the lower crust uplift. This layer follows a not very stable trend regarding basement depth.

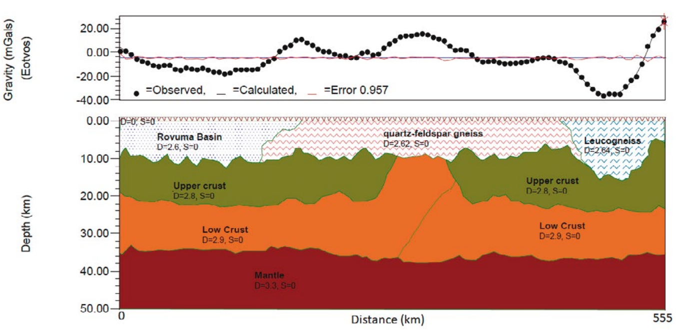

Figure 10. The crustal model generated from the A-A' representative profile. The dotted black curve represents the observed anomaly, the black curve represents the calculated anomaly, and the red curve represents the error between the calculated and observed data.

4.2.2. Profile B-B'

In figure 12, we present the crustal model for the B-B' profile, with density distribution in the subsurface. This model has its origins in the northeast of Niassa and extends to the province of Nampula. The profile starts with a relatively low gravity signature (-13.5 mGal) reaching a high gravity (36.6 mGal) along the profile, which possibly these high values are found at the intersection of the three provinces.

These high anomalies may be due to the presence of high-grade metamorphic, ultrabasic,and basic igneous rocks, which predominate in these two large complexes that outcrop in the area. This model consists of four layers limited by three interfaces: three layers belonging to geological units, crust (upper and lower), and the fourth layer representing the mantle.

The geological units have a variable thickness in the direction of the profile. These geological units show three portions within the first layer section, there is a portion with granitic to granodiorite gneiss (north of the section), migmatites and a portion with leucogneisse (south of the section). The second layer, referring to the upper crust, has a thickness ranging from 12 to 28 km. In the Niassa region, the crust tends to outcrop on the surface. The central region of the profile presents a thinning of the upper crust. The fourth layer, referring to the lower crust, presents not very coarse variations in thickness, between 32 and 36 km.

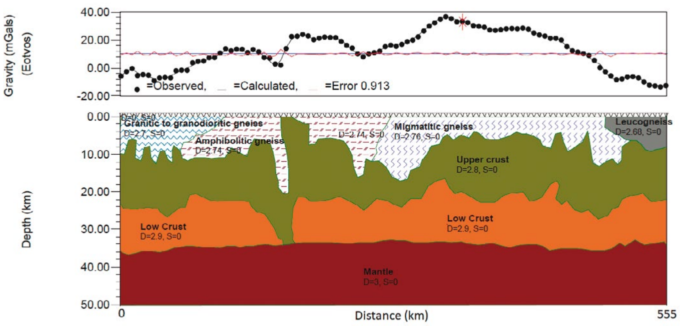

Figure 11. The crustal model generated from the B-B' representative profile. The dotted black curve represents the observed anomaly, the black curve represents the calculated anomaly, and the red curve represents the error between the calculated and observed data.

4.2.3. Profile C-C'

In figure 13 we present the crustal model for the C-C' profile, with density distribution in the subsurface. Again, this profile comprises the provinces of Niassa and Nampula. In this model, the profile sections the Unango Complex from the north side of the profile to the Nampula Complex towards the south side, these two complexes are the oldest in terms of geochronology, with a predominance of rocks that underwent medium to high-grade metamorphism. The profile of this model has a minimum gravity of -60.9 mGal, possibly due to the influence of acidic rocks that outcrop in the area or high depth and the maximum anomaly of 19.4 mGal, may be due to the influence of basic rocks and crust uplift bottom.

The model extends from north to south of Niassa, showing the thicknesses of each layer. The first layer, which corresponds to the geological units, varies around 12 to 14 km. However, the second layer that represents the upper crust shows great variations and a very noticeable thinning in the Nias-sa province, and a crustal thickening is verified in the following regions, the upper crust has a thickness varying from 12 to 20 km. The third layer, which is the thickest of all, referring to the lower crust, its thickness varies between 24 to 40 km.

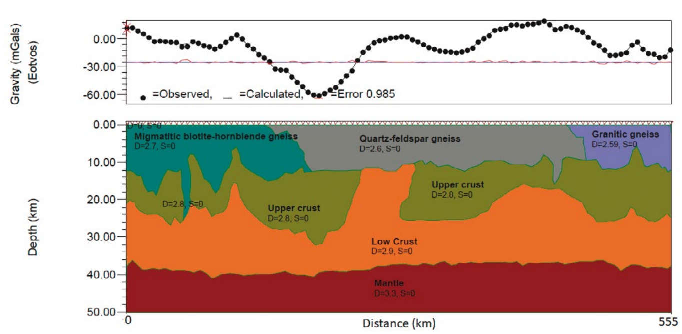

Figure 12. The crustal model generated from the C-C' representative profile. The dotted black curve represents the observed anomaly, the black curve represents the calculated anomaly, and the red curve represents the error between the calculated and observed data.

4.2.4. Profile D-D'

Figure 13 shows the crustal model for profile D-D', displaying the density distribution in the subsurface. This profile covers the Niassa and Nampula provinces. These two complexes exhibit the most remote geochronology, being predominantly composed of rocks that have undergone medium to high grade metamorphism of a more mafic character.

The model reveals an interesting gravimetric signature, comprising both positive and negative anomalies. Notably, the positive signatures are mainly concentrated in the Marupa tectonic unit, represented in the profile by the Granite lithotype. In contrast, the other geological units are characterized by lower gravimetries, manifesting negative signatures that are associated with the Loucognaisse and quartz-feldspar lithologies. These gravimetric variations, both high and low, are correlated with the different depths observed along the profile for each of the geological units.

The first layers correspond to the main units of the geotectonic domains, whose thicknesses vary between 4 and 16 km. The Marrupa geological unit and the northern part of the Nampula Complex are characterized by a low depth/thickness, with values around 4 to 6 km. On the other hand, the other units located at the extremities of the profile (model) have greater depth, ranging from 10 to 16 km.

The second layer represents the upper crust, and shows remarkable variations along the profile. It is possible to observe that the thickness of the upper crust is greater in Niassa Province and decreases progressively towards Nampula Province. This gradual reduction is closely related to the fact that this region corresponds to a passive margin.

The third layer is called the lower crust which is the densest structure. It presents a similar behavior, as it is also greatest in the Niassa province and gradually reduces towards Nampula. Although the maximum thickness value, reaching 38 km, is observed in Niassa, there is also a remarkable variability along the profile, showing that there is no crustal consistency or stability in terms of thickness. In other words, the Moho shows significant variations along the profile.

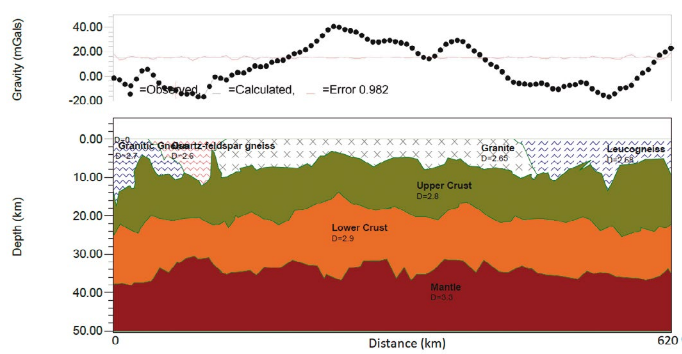

Figure 13. The crustal model generated from the D-D' representative profile. The dotted black curve represents the observed anomaly, the black curve represents the calculated anomaly, and the red curve represents the error between the calculated and observed data.

5. Discussion

This study aimed to map the thickness of the crust and lithosphere for the northern region of Mozambique using topography, geoid anomaly and gravity data. One of the major gains from this study was to present for the first time the crustal (Moho) and lithospheric (LAB) thickness maps in the most local context and to compare these results with previous studies. The genesis of the crustal and lithospheric configuration of the study region is associated with the separation of the African and South American Plates initiated by the breakup of the Gondwana Supercontinent in the Mesozoic era, in the Triassic period. A study by Macey et al. (2013), reports that the crust in northern Mozambique is divided into two similar but different tectonic blocks. It is reflected in the crustal thickness values obtained from our calculations, which show variations but with some similarities in some geological units (Fig. 8). The architecture and geological evolution of the crust is explained by two models, the first one being involves the convergence of eastern and western Gondwana associated with the closing of the Mozambique Ocean along the East African Orogen and the is related to the two-stage melting of the components of Gondwana which are the collision between the eastern and western components of Gondwana, and the collision of the newly formed northern block of Gondwana with a southern block of Gondwana (2013).

Our results are satisfactory and agree with Globig et al. (2016). These authors used geoid anomaly and topography data associated with thermal analysis to map the crust and lithosphere thickness of the African continent. Their results imply that the northern region of Mozambique has a crust that varies from 29 to 40 km in thickness and a maximum lithospheric thickness of 180 km. These results agree with ours, as ours reveal that the crust varies between 27 and 39 km, while the lithosphere varies between 150 and 195 km. Furthermore, these authors report that, generally, the thick crust (>37 km) is associated with the Archean cratons and shields and with the Proterozoic belts. The northern region of Mozambique is part of the Mozambique belt with a maximum Moho geometry of about 40 km, as shown in figure 5a. The crustal gravity models of the northern region of Mozambique showed good correlations for the Moho depth that varies from 35 to 40 km, according to similar works presented by Araújo (2018) and Fries (2003) of the crust thickness.

In general, our Moho results can be seen from three perspectives: first, thicker continental crust (33- 39 km) is observed in the Unango and Formation tectonic domains that are located in the western region of Nissa province. Second, intermediate crust (31–33 km), which is observed in the Xixano, Marrupa, Muaquia and M'Sawize tectonic units, and also west of Nampula province which are located in the eastern region of Niassa province and west of Cabo Delgado province. And finally, transitional crust which is thinner (27-31 km), being in the transition zone between ocean and continent, and comprises the tectonic units Ocua, Recent formation (Rovuma sedimentary basin), Lalamo, Meluco, Nairoto in the eastern region of the province of Cabo Delgado and Nampula to the east. Regarding LAB, the most notable results reveal that the lithosphere in this region can be divided into transitional lithosphere, which is less thick and is located mainly in the Recent formation (Rovuma sedimentary basin), Lalamo and Meluco tectonic units of Cabo Delgado province, whose thickness between 150 to 165 km. The other geological units of Niassa and Nampula provinces are characterized by a thicker lithosphere ranging from 165 to 195 km.

The profile A-A' has a length of 555 km, oriented in the N-S direction, and crosses five geological units/complexes, namely: Rovuma Basin (Recent Formations), Montepuez, Lalamo, Ocua and Nampula. In the model, the Lalamo, Montepuez and Ocua units were grouped into a single geological body/structure due to the similarity of the lithologies and tectonic history of these complexes. In this profile, small variations in the thickness of the upper and lower crust are noted, with the most significant highlight being the uplift of the lower crust towards the base of the complexes along the profile. This uplift may be associated with one of the tectonic events that occurred in the area, as presented by Macey et al. (2013), which involves the convergence of eastern and western Gondwana, associated with the closure of the Mozambique Ocean along the East African Orogen. Finally, the maximum values of crustal thickness reach 37 km due to the proximity of the region to the oceanic coast, which has a lower depth of the Moho. Like the A-A' profile, the second profile, named B-B', has a length of 555 km and covers four main geological units, namely Marrupa, Ocua along the Lúrio belt, Nampula and extends into the central region of Mozambique, in Zambézia province. The geological structures presented in the middle part of the profile exhibit higher density, comprising formations such as Amphibolite and Migmatite. Such bodies probably result from the convergence process of eastern and western Gondwana, associated with the closure of the Mozambique Ocean, as indicated by Macey et al. (2013). This tectonic event may have been responsible for the generation of intrusions in these formations.

In addition, a variation in the thickness of the upper crust is observed along the profile, with a notable uplift. This feature contrasts with the previous profile, where the uplift was more related to the lower crust. Additionally, this uplift may be related to the collision between the East and West components of Gondwana, forming the East African orogen, with N-S orientation, and in northern Mozambique, the formation of accretionary terrains, as proposed by Macey et al. (2013). Another hypothesis involves the collision of the northern block of Gondwana with the southern block, also encompassing the collision of the Australia and Mawson blocks (Macey et al., 2013). The average crustal thickness in this region is 36 km, however, a slight reduction in thickness is observed below where we have the Amphibolite and Migmatite geological bodies.

The profile C-C' is equally significant, covering a distance of 555 km, similar to the first two profiles mentioned above. This profile comprises three distinct geographical regions, namely Lake Niassa, located in the west of Niassa Province, and Unango and Zambezia, located in the center of the country. This arrangement is discernible when analyzing the portion of the profile that transcends the boundaries of the Unango unit (Figure 6). The results obtained from our investigation reveal notable variations in crustal blocks, both in the upper and lower layers. Notably, the uplift of the lower crust is observed, which seems to be associated with the same tectonic events presented in the first two profiles previously examined. It is worth noting that the main distinction of this profile lies in the values concerning the Moho, since its westernmost location, adjacent to the Niassa Province.

The profile D-D' stands out as the most remarkably distinct among all, both for its W-E orientation and for its length, totaling 620 km. This profile crosses four important geological units, namely Unango, Marrupa, Ocua and Nampula. The results obtained from our analysis reveal a highly variable crustal thickness along the profile, both in the upper and lower layers. The western region exhibits a thicker crust, reaching a maximum thickness of 38 km, while in the eastern direction, corresponding to the coastal region, the crustal thickness tends to decrease. It is important to highlight that in this coastal region, the gravimetric signature of the crust is more positive, being congruent with the geological units of Marrupa and Ocua. These domains are associated with the Lúrio belt, and geophysical data at regional-scale with NE-SW trend, forming in response to progressive deformation experienced.

In the NW portion of Messuli Point, along Lake Niassa, a 1.9 Ga Palaeoproterozoic basement is exposed, overlain by the Txitonga Group, known for its low-grade metasediments (Viola et al., 2006). The Unango, Marrupa and Nampula complexes were influenced by Pan-African metamorphism (Viola et al., 2008), and as observed in other profiles, are characterized by positive gravimetric signatures. Therefore, our results corroborate the proposition of Viola et al. (2006), who pointed to the E/ENE-W/WSW trend in the crust in this region.

The profiles modeled in this work possibly show that they are located in the continental crust collision zone according to Afonso, Marques, & Ferreira, 1998, in their book on the Geological Evolution of Mozambique. The profiles have a high gravity value that would correspond to the obduction represented by basic and ultrabasic rocks. On the contrary, the genesis of pan-African orogenic sets would be due to post-collision volcanism (Nédelec et al., 1994 as cited in Afonso, Marques, & Ferreira, 1998). Thus, the lithologies present in the orogenic sets would have their origin in the magma resulting from the crustal fusion related to the shear effects, and fill the sutures resulting from the collision of the continental blocks.

The convergence of the East and West Gondwana terranes, associated with the closure of the Mozambique Ocean, resulted in extensive metamorphism processes in these large blocks, characterized by increased temperature and pressure. This generated strong compositional banding and significant increase in rock density. These high-grade metamorphic rocks are the result of collisional orogenies followed by late tectonic intrusions, as observed in the Bouguer anomaly map.

6. Conclusion

The text discusses a study conducted to map the crust and lithospheric thickness in the northern region of Mozambique using gravity data, geoid anomaly, and topography. The authors employed regional-residual separation techniques to analyze the gravity data. For Regional-Residual Separation, the regional Bouguer anomaly map showed an increase in gravity signal in the NW-SE direction, reflecting deeper geological features with low frequencies and high wavelengths. The residual Bouguer anomaly map highlighted shallow geological structures with strong gravity signals due to higher frequencies and shorter wavelengths.

For the Crustal Thickness, the northern region of Mozambique is divided into three provinces: Niassa, Nampula, and Cabo Delgado. Niassa province exhibited high values of crustal thickness (Moho depths) ranging from 33 to 39 km, increasing from east to west. Nampula and Cabo Delgado provinces had thinner crusts, varying from about 27 to 35 km. And for the Lithospheric Thickness, the lithospheric thickness (LAB) showed thinner lithosphere in Nampula and Cabo Delgado provinces (150 to 165 km) and thicker lithosphere in Niassa province (165 to 195 km), increasing from east to west due to the proximity to the oceanic shelf.

For the Density Distribution, the mean density distribution in the lithospheric mantle revealed denser lithosphere adjacent to the ocean shelf in parts of Nampula and Cabo Delgado provinces (approximately 3250 kg/m^3) and less dense lithosphere in Niassa province (3240 to 3250 kg/m^3).

On the Gravity Direct Modeling, the gravity modeling involved four representative profiles (A-A', B-B', C-C' and D-D') in the study area. The models provided insights into the geological units and depths of the crustal and lithospheric layers along the profiles.

The gravity models revealed variations in crustal and lithospheric thicknesses in different geological units, reflecting the complex tectonic history and collisions of continental blocks in the region.

The results generated by the study are consistent with previous research, validating the crustal and lithospheric thickness values obtained for the region.

In summary, the study successfully mapped the crustal and lithospheric thickness in the northern region of Mozambique and provided valuable insights into the geological evolution and tectonic processes that shaped the area. The findings of this study are vital in understanding the region's geology and tectonics.

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