Cartographic Scripting for Geophysical Mapping of Malawi Rift Zone

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This paper describes a scripting cartographic techniques that automatically generate maps from open source spatial data using syntax of General Mapping Tools (GMT) and R. A case study present mapping East Africa with a focus on Malawi. In this study, two different approaches of scripting cartography using R programming language and GMT were studied for geophysical analysis aimed to visualize a series of eight new maps in Malawi: topography based on the GEBCO data, seismicity, geomorphometric modeling based on SRTM-90 m (slope, aspect, hillshade and elevation) and geophysical fields: geoid based on EGM-2008 and free-air Faye's gravity based on satellite derived gravity data from CryoSat-2 and Jason-1. In contrast to previous maps of Malawi, a scripting approach was introduced as a console-based cartographic mapping developed for plotting a series of thematic maps based on the high-resolution data. The maps demonstrate correlations between the topography and tectonic faults (Malawi Rift Zone) and earthquakes in the Malawi Lake and extent of landforms. The results demonstrate strong correspondence between the topography and geophysical fields (geoid and gravity): negative values of geoid (-15 to -20) are notable over the Malawi (Nyasa) Lake which corresponds with local topographic depressions. Free-air gravity fields reach the lowest values (-50 to -100) over the Malawi Lake. Local heights in gravity are compared with topographic mountain ranges in the NW and SW of the country on the borders with Zambia and Mozambique. The location of earthquakes vary with the majority located in the north. The geomorphological landforms demonstrate variability in slope steepness and aspect orientation shown on histogram. The techniques of scripts can be used to automatically map spatial data using raster datasets for geophysical visualization, and this paper demonstrated this through a variety of map from the presented thematic series of geophysical maps of Malawi. Full scripts used for mapping are available on the author's public GitHub repository with provided link to her open access codes.

Key Words: *Africa, geophysics, shell script, R, gravimetry*

1. INTRODUCTION

The present paper is focused on the study of geological and geophysical setting of Malawi using advanced methodology of scripting cartography. Visualization of topographic and geophysical data is crucial for understanding physical geography of the country, seismicity, geomorphology, and geology. Malawi, located in the Great Rift Valley is notable for varied geological setting created as a result of long evolution of the East Africa. Malawi is sensitive to natural hazards of climate (floods, droughts, strong winds, hailstorms) and geologic origin: landslides, volcanoes and earthquakes.

Accurate visualization of the geologic, topographic and geophysical data using modern cartographic tools is important. It allows to identify the on-going geophysical processes in such seismically active and geologically complex region as Malawi, provide up-to-date maps and charts to assess possible consequences of the seismic events, analyse their frequency, magnitude and focal depths and bring raw data for environmental modeling and management of the country located in the Great Rift Valley.

Mapping geophysical fields of gravity anomalies is valuable to understanding its correlation with topography and geology as reflected in the density of the underlying rocks. Using advanced methods of data visualization have direct implications in general

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development of the GIS methods and mapping approaches that can be applied in similar works. A number of environmental studies with mapping using GIS are available [1–3].

However, when compared to the scripting methods of Generic Mapping Tools (GMT), it presents methodological improvements due to automation of data processing through scripts [4, 5]. Specifically, applying scripting methods for mapping (several modules of GMT and packages of R, plus open source datasets) is beneficial for cartographic workflow. Implementation of scripting algorithms for raster data visualization and image processing, vector data plotting and mapping was performed by GMT and R.

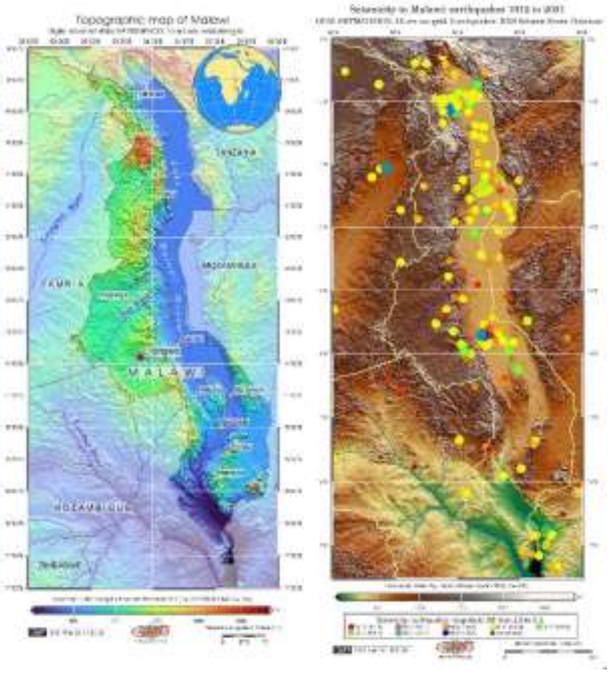

Figure 1 - Topography and earthquakes distribution in Malawi. Mapping: GMT. Source: author.

Another aspect consists in the open datasets of various origin used for processing and mapping. Reliable data enables to analyse and assess the complexity of the geophysical setting and its relation with topography and geology. Complex cartographic analysis requires multi-source data processing which should, based on availability, include geomorphological, topographic, geological and tectonic data. Contemporary data (GEBCO, SRTM, EGM-2008 and DCW) provided core materials for mapping in this research using global grids selected for the spatial context of Malawi.

The case study presented in this paper discusses a solution that combines the open source GMT with the programming language R for the multi-source mapping of Malawi. Taking into account the correlations between the geological and tectonic setting of Malawi reflected in topographic relief, a wider integrated cartographic method combining R and GMT scripting tools to visualization of Malawi is crucial to grasping such complexity.

From a mapping perspective, the approach of conventional geospatial software displays datasets using straightforward yet very limited techniques of the menu-based GIS. In contrast, the scripting-based approach presented much more flexible technically and sophisticated aesthetically console-based cartographic techniques. Using scripting, highly similar to the programming languages, is a fundamental concept of GMT.

A technical combination of the two various methods (GMT and R) makes mapping process finely adjustable to take the advantages of each method from its best functionality: using R packages 'raster' and 'tmap' for a combined geomorphometric modeling and a set of GMT modules for geophysical mapping. Through a more methodologically and technically rooted approach, R packages 'raster' and 'tmap' presented an evaluation of spatial data for mapping rather than operating with non-spatial data as is a usual application of scripting languages. Thence, the principal novelty of R in this research consists in its application to the cartographic workflow rather than for traditional coding as used in the IT (programming) domains.

Moving R beyond programming as a purely coding tool towards cartographic data processing, this paper proposes a practical interpretation of the DEM-based dataset (SRTM-90) as the input material to model four various geomorphometric derivatives of the relief of Malawi: slope, aspect, hillshade and elevation. Combined with GMT as mixed-method of cartographic data visualization, this paper uses high-resolution data for geophysics (geoid, free-air gravity), topography, geomorphology and seismicity of Malawi, which combines scripting approach with geological analysis of the country. Thence, the present approach achieves an integration of the qualitative and quantitative data analysis through visualization.

2. MATERIALS AND METHODS

To compile the contemporary topographic, seismic and geophysical setting of Malawi, this research applied open source spatial datasets, processed by GMT and R. Full scripts used for mapping are available on the author's GitHub repository: https://github.com/paulinelemenkova/Mapping_Malawi_R_GMT_Scripts

2.1. Data

The data used for GMT-based mapping include General Bathymetric Chart of the Oceans (GEBCO) [6, 7]. GEBCO data presents the updated and comprehensive topographic data of the Earth, regularly updated and publicly available:

https://www.gebco.net/ GEBCO is widely used in geoscience [8–16]. The geophysical gravity grid (Fig. 4b) was taken from the available data developed based on satellite derived geophysical observations from the CryoSat-2 and Jason-1 sources [17]. The geoid undulations (Fig. 4a) were modelled using the Earth Gravitational Model EGM-2008 [18].

The seismicity has been mapped using the IRIS data base (http://ds.iris.edu/seismon/index.phtml) with data captured on the Malawi extent and stored in a tabular format (.csv) and then read into the GMT through conversion to the readable (.ngdc) format. The data show earthquakes magnitude visualized by colours using ‘seis’ colour palette.

The SRTM90 data embedded by R were downloaded into the RStudio environment using the functionality of „raster“ package as a reference input the Digital Elevation Model (DEM) data for geomorphometric mapping (Fig. 2 and 3) in order to assess the topographic characteristics (slope, aspect and hillshade modeling) of the Malawi topographic relief. These materials were applied as basic source input raw geodata to provide contemporary spatial extent and topographic, geophysical and geologic setting of Malawi supported by the literature review on relevant publications describing the physical geography, topography and geology of Malawi [19–24].

2.2. Cartographic plotting in GMT

The Generic Mapping Tools (GMT) part of this work (Fig. 1 and Fig. 4) has been prepared using GMT scripting toolset [25]. The difference of GMT from the traditional GIS [26–31] consists in the console which enables interactive mapping that combines coding, visualization of cartographic images and graphs, and plotting textual annotations on the graphics [32].

The GMT mapping is based on scripting, which enable the elements-oriented design paradigm with possibility of plot each cartographic element by a specially designed GMT module as a part of the script. Thus, the following techniques were utilized for plotting the maps in Fig. 1 (left for topography and right for seismicity):

- a subset of the GEBCO grid was extracted for the region of Malawi: „gmt grdcut GEBCO_2019.nc -R32/36/-17.5/-9 -Gmw_relief.nc“ and checked by GDAL for topographic extremes: „gdalinfo -stats mw_relief.nc“ (Min=36.00, Max=2846.00).
- The color palette has been adjusted to the elevation heights as follows: „gmt makecpt -Cdem2.cpt -V -T36/2846 > pauline.cpt“.
- The clipping of the area was done using the available embedded layer of Digital Chart of the World (DCW), which is a comprehensive digital data of Earth by the „pscoast“ module: „gmt pscoast -R32/36/-17.5/-9 -JM5.0i -Dh -M -EMW > Malawi.txt“
- The volcano points (red triangles in Fig. 1, right) were added using ‘psxy’ module: ‘gmt psxy -R -J volcanoes.gmt -St0.4c -Gred -Wthinnest -O -K >> $ps’.

Likewise, similar structure of scripts was applied for plotting Fig. 4 (left for geoid and right for free-air gravity) using the following most important combination of codes:

- Visualization of the image by ‘grdimage’ module: ‘gmt grdimage geoid_MW.grd -Ccolors.cpt -R32/36/-17.5/-9 -JM5.0i -P -Xc -K > $ps’
- Plotting isolines of geoid every 0.5 m using the following code: ‘gmt grdcontour geoid_MW.grd -R -J -C0.5 -A1+f9p,25,black -Wthinner,dimgray -O -K >> $ps
- Adding the contour linde sof countries and river netweork: ‘gmt pscoast -R -J -P -Ia/thinnest,blue -Na -N1/thickest,purple -Wthinner -Df -O -K >> $ps’
- Extracting subset of img file for the free-air gravity: ‘gmt img2grd grav_27.1.img -R32/36/-17.5/-9 -Ggrav.grd -T1 -I1 -E -S0.1 -V’
- Converting img into grd file: ‘gmt grdcut grav.grd -R32/36/-17.5/-9 -Gmw_grav.nc’
- Adding GMT logo: ‘gmt logo -Dx5.0/-3.0+o0.1i/0.1i+w2c -O -K >> $ps’

2.3. Modelling in RStudio

The maps plotted in Fig. 2 and 3 for geomorphometry of Malawi have been plotted using R programming language [33] using RStudio. Specifically, the case study utilized 'tmap' [34] and „raster“ [35] libraries of R, as these packages are designed for geomorphometric analysis and cartographic visualization using the scripting language of R as a geospatial application.

Both „tmap“ and „raster“ support general syntax of R, with existing application in research [36, 37]. The „tmap“ and „raster“ are the two developed R libraries for handling geospatial data based on general R data analysis approach.

The „raster“ library provides a wide functionality for cartographic modelling which lends itself to processing of spatial raster grids DEM (SRTM based) datasets as cartographic layouts with possibility of modelling: slope analysis, aspect analysis and hillshade with artificially illuminated light source for effective visualization of the topography.

The „tmap“ library presents more sophisticated possibilities of cartographic data handling and adjusting aesthetics through a variety of functions with defined flags.

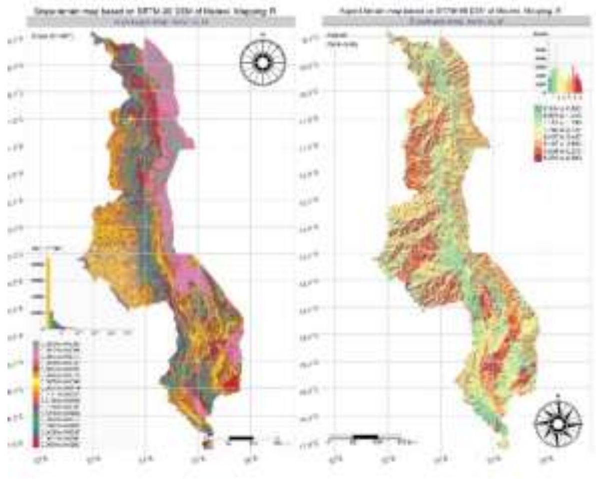

Figure 2 - Slope and aspect terrain visualization of Malawi. Mapping: R. Source: author.

Besides these two major packages, the auxiliary libraries used in this research include the following tools: library(ncdf4) used for data format handling, library(RColorBrewer) used for color palette selection, library(sf) used for operating with Simple Features through as a standardized way to encode spatial vector data. The library(sp) implements dedicated classes for and methods for spatial data. The classes record where spatial location information resides for 2D or 3-D data that enables interacting with geodata as spatial objects.

Since 'raster' package generates an access to the Shuttle Radar Topography Mission (SRTM) with 90 m resolution containing elevation data, the data were captured through the 'getData()' function. Thus, the DEM data were downloaded for the whole country of Malawi using the code: ‘alt = getData("alt", country = "Malawi", path = tempdir())’. Afterwards, the data were modeled using the set of following codes: 'slope = terrain(alt, opt = "slope")', 'aspect = terrain(alt, opt = "aspect")' and 'hill = hillShade(slope, aspect, angle = 40, direction = 270)'.

In the following step, the modelled data were visualzied using the 'tmap' package by the set of functions: 'tm_shape', 'tm_raster', 'tm_scale_bar', 'tm_compass', 'tm_layout' and 'tm_graticules' using the adjusted settings. The sidewise arrangements of maps (Fig. 2 and 3) was performed using the 'tmap_arrange' function: 'Twomaps <- tmap_arrange(map1, map2).

The visualization of each resulting pair was done by calling the map: ‘Twomaps’. Afterwards, the raster image was saved by ‘tmap_save’ function: ‘tmap_save(Twomaps, "Malawi_SlopeAspect.jpg", dpi = 300, height = 10, width = 12)’.

3. RESULTS AND DISCUSSION

Figure 1 (left) shows the topographic setting of the Malawi mapped using GEBCO 15 arc-second resolution grid. Geomorphologic landforms (mountains, floodplains or fluvial relief), mechanics and dynamics of the processes of their formation, gravity and magnetic anomalies, undulations in geoid model, location of ecological habitats and local climate variations are all – to a lesser or greater extent – influenced by or reflected in topography, which explains the importance of the topographic mapping (Fig. 1, left). Considering complex correlation between the topography and processes and phenomena reflected on the shape of the Earth (geology, climate, environment and geomorphology), advanced cartographic approach to modelling data is key to system understanding.

Fig. 1 (right) shows the main seismicity setting of the Malawi region mapped using IRIS database. Specifically, it visualizes the distribution and magnitude (by colours) of volcanoes over the study area. The volcanism within the Rungwe Volcanic Province began in late Miocene time (the Neogene Period of Cenozoic Era). Besides, evidence of six eruptive episodes within the nearby Rungwe Volcanic Field between ca. 9000-360 BP was recorded in the ash horizons in Holocene sediments from northern Lake Malawi [38]. The locations of eruptive volcanic centres in the Rungwe region is largely controlled by the distribution of the tectonic faults. These centres are mostly extended northward along the transfer faults during Pliocene (Late Neogene) and Pleistocene of Quaternary [39], which is well reflected in the map with visible concentration of volcanoes and earthquakes in the north of the Malawi Lake. Seismic events of varying magnitudes correlate with ruptures along the buried faults of Malawi [40].

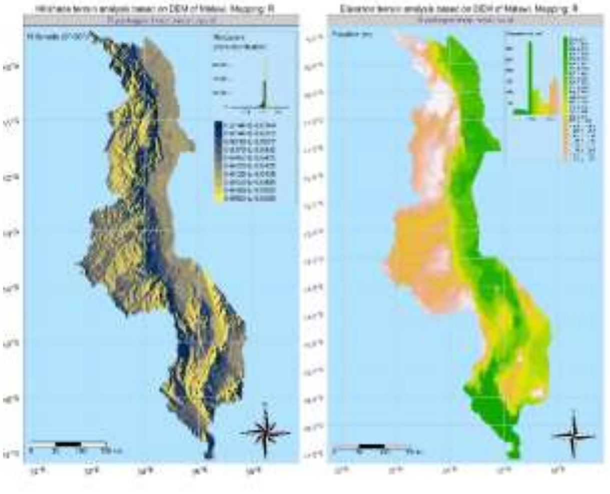

Figure 3 - Hillshade and DEM SRTM90 terrain map of Malawi. Mapping: R. Source: author.

More active earthquakes are also associated with the northern region of the Malawi Lake, as could be illustrated by the shallow earthquake sequence in the

Karonga region of northern Lake Malawi in December 2009. The more active seismicity in northern Malawi (Fig. 1, right) can be explained by the more active tectonic, geophysical and geological setting. There is crustal thinning in the asymmetric basins of northern Malawi rift, focused beneath the centres of rift basin segments, which correlates with models of rift flank topography and gravity observations, as seen in Fig. 4.

Fig. 2 shows the geomorphometric mapping of the Malawi with visualized slope (left) and aspect (right) of its relief. Among the most notable geographic features of Malawi one should mention the following most important landmarks: 1) Nyika Plateau located in northern Malawi, with prevailing elevations 1950–2450 m [41] and covered by the low-canopy montane forests with elevation of >2250 m [42]; 2) Shire Highlands located in the southern Malawi, east of the Shire River with dominating heights at 600–1100 m [43]; 3) Mulanje Massif (southern Malawi) which has a steep topography covered by precious cedar forests and other endemic flora [44]; 4) Mafinga Hills located in the eastern Malawi; 5) Kirk Range located in the souther-western Malawi which presents a mix of miombo woodlands on the lower slopes and grasslands, and shrublands in the higher elevations and other types are composed of various structurally distinct vegetation communities, savannas and grassland among others [45].

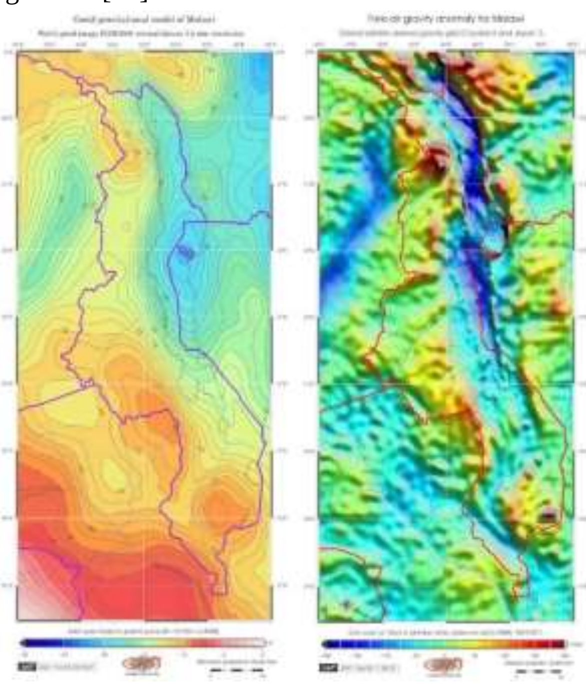

Figure 4 - Geophysical fields mapping: geoid and free-air gravity models of Malawi. Mapping: GMT. Source: author.

Figure 3 shows the DEM based (SRTM90) modelling of hillshade (Fig. 3, left) and of the elevations in Malawi (right) derived from the geomorphometric mapping using R. The geomorphology of the region is largely reflecting the tectonic processed that took place in the area in the past. Thus, tectonically, the Malawi Rift is located at the southernmost segment of the Western Branch of the East African Rift System.

The Karoo sediments were deposited between the Late Carboniferous and Early Jurassic and accumlated under the influence of two main factors: dominating tectonism and additional climate. Besides, the sediment accumulation is also affected by the eustatic influence caused b the gradual decrease in topographic slope during orogenic loading, that is, topographic factor [46]. In Malawi, the Karoo rift basin was formed under the influence of two distinct tectonic regimes of the southern and northern margins of Gondwana and evolved during the breakup of Pangea [47].

Spatial topographic variations are reflected in the pattern of the sediment distribution in the Malawi Lake which varies in its different parts. For instance, thick sediments are noted in the border-fault bounded rift basin. The sedimentation and geochemistry in the Lake Malawi (Nyasa) is largely influenced by the variety of factors: Quaternary tectonic activity, geophysical processes (heat-flow), hydrological and hydro-chemical (major elements, stable isotopes) factors [48]. Fig. 4 shows the geophysical setting of the Malawi with visualized geoid undulations (left) and free-air gravity (right).

4. CONCLUSION

For moving mapping beyond the traditional GIS, scripting-based cartographic approach emerged as a novel technique for its ability to combine geospatial visualization in terms of cartographic output (maps) with programming algorithms and principles of data processing by a console [49, 50], without GUI which is traditional for GIS.

Compared to the traditional GIS, the mixed-method approach anchored in scripting (R and GMT) delivered two major advantages: i) technically, the research presents more sound outputs in terms of cartographic plotting and data modelling; ii) mix of the multi-source data enables wider and deeper understanding of the geophysical and tectonic complexity and seismic variability in such tectonically active region as Malawi, located in the East African Rift System [52].

Scripts in cartography are important:

(1) Free open source tools, GMT and R are available for every researcher and/or student including those practicing distance/home-based research. This is a significant advantage compared to the commercial GIS where a license is required;

(2) Scripting techniques enables effective data pro-

cessing through the ready-to-use templates of scripts. This results in the increased level of automatization in data processing;

(3) Ontological and theoretical contribution arises as a consequence form the previous statement: the increased level of the machine-based data processing largely contributes to the generation of new data, updated maps and dissemination of knowledge on seismicity and geophysics using actual data derived from IRIS.

Altogether, using scripting approach in mapping makes it possible to refine thematic analysis (geologic, geophysical and geomorphological) through technically updated visualization by advanced methods. Effective visualization in geological mapping and monitoring natural hazards consists in the ability to highlight correlations between physical geographic phenomena, topography and distribution of objects in space which enables to visualize seismic events, make a prognosis, assess topographic situation using robust data, predict and monitor droughts using precise climate data. These are all possible using reliable data and high-quality maps.

To conclude, the rise of the programming era in 20th century and its and rapid development in 21st century results in a wide variety of languages, scripting libraries and possibilities to process data [53, 54]. This includes not only the tabular data but also the geospatial coordinate-based data. The power of programming approaches largely influences both technical cartographic plotting and conceptual aspects of data processing. This paper contributed to the cartographic scripting and presented a case study of the Malawi Rift Zone.

5. ACKNOWLEDGEMENT

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REZIME

GEOFIZIČKO POSTAVLJANJE I SEIZMIČNOST U ZONI RIFT MALAVI, JUGOISTOČNA AFRIKA, ANALIZIRANO KARTOGRAFSKIM SKRIPTIRANJEM

Vizualizacija ili modeliranje kartografskih podataka je presudno za geološko mapiranje u seizmički aktivnom Malaviju, na jugoistoku Afrike. IRIS U ovoj studiji proučavana su dva različita pristupa skriptovanju kartografije korišćenjem programskog jezika R i Generic Mapping Tools (GMT) kako bi se vizualizovala serija od osam novih karata u Malaviju: topografija na osnovu podataka GEBCO, seizmičnost zasnovana na katalogu IRIS za 1972-2021), geomorfometrijsko modeliranje zasnovano na SRTM-90 m (nagib, aspekt, padina i nadmorska visina) i geofizička polja: geoid zasnovan na EGM-2008 i Faie-ova gravitaciona baza slobodnog vazduha na osnovu satelitskih podataka izvedenih gravitacionih podataka iz CryoSat-2 i Jason-1. Za razliku od prethodnih mapa Malavija, pristup skriptiranju predstavljen je kao kartografsko mapiranje zasnovano na konzoli razvijeno za crtanje niza tematskih mapa na osnovu podataka visoke rezolucije. Mape prikazuju odnose između visina i tektonskih rasjeda (zona Rift Malavi), distribuciju seizmičkih događaja i vulkana na severu jezera Malavi i obim reljefa. Rezultati pokazuju snažnu korelaciju između kota i geofizičkih polja (geoid i gravitacija): negativne vrednosti geoida (-15 do -20) primetne su nad jezerom Malavi (Njasa) koje odgovara lokalnim topografskim udubljenjima. Gravitaciona polja slobodnog vazduha dostižu najniže vrednosti (-50 do -100) iznad jezera Malavi. Lokalne visine gravitacije se upoređuju sa topografskim planinskim lancima na SZ i JZ zemlje na granicama sa Zambijom i Mozambikom. Raspodela seizmičkih podataka pokazuje varijabilnost sa izrazitim porastom podataka na severu zemlje. Geomorfološki oblici reljefa pokazuju varijabilnost u strmini kosine i orijentaciji aspekata prikazanih na histogramu. Rad doprinosi regionalnim geofizičkim studijama Malavija i predstavlja osam novih karata.

Ključne reči: *Malavi, Afrika, kartografia, zemljotresi, skripta ljuske, GMT, R, geofizika*