Tanzania Craton, Serengeti Plain and Eastern Rift Valley: mapping of geospatial data by scripting techniques

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Abstract. Cartographic visualization is a key means for the analysis of the Earth's environmental processes. In view of the rapidly increasing multi-source data, cartographic approaches are updated accordingly. Mapping of countries characterized by complex geologic settings, such as Tanzania, requires implementation of advanced approaches. Cartographic solutions for the best visualization aim to provide elaborate content in an understandable and interoperable way in multi-disciplinary studies. This study presents such an approach by using Generic Mapping Tools (GMT), R and QGIS for cartographic mapping of Tanzania, with five maps addressing the natural setting (geology, topography, geophysics) and four maps showing the geomorphometric analysis. The 2D maps and the 3D mesh model were made by the traditional Geographic Information System (GIS) and scripting approaches. The features of the geomorphometric maps (slope, aspect, hillshade, elevation) were plotted by means of R. The technical methods are illustrated by the example of scripts. The paper contributes to the regional studies of Tanzania.

Keywords: GMT, R, QGIS, Tanzania, cartography.

INTRODUCTION

An increasing volume of data is being generated by the geological surveys and remote sensing carried out in Tanzania (Temple and Rapp 1972; Kagya et al. 1991; Mjili and Mulibo 2018; Mvile et al. 2020). The need for rapid and effective processing of the collected data drives the search for effective tools for cartographic workflow with minimized handmade routine and maximized automated approach. The scripting approach in cartography enables to better explore geological and geomorphological data.

The environmental setting of Tanzania (see Fig. 1 for topography) has been continuously studied since the 1960s (James 1967; Kent et al. 1971; Kajato 1982; Maboko and Basu 1987; Ijumulana et al. 1997; Kabete et al. 2012a, 2012b; Boniface 2014; Hamdun and Arakaki 2015; Gombe et al. 2017; John 2020). Such attention can be explained by its unique environment, specific geologic setting and rich mineral resources. Tanzania is notable for unique natural settings influenced by the East African Rift, an intra-continental active ridge system (Bosworth et al. 2000; Chorowicz 2005; Kapilima 2003). Geologically, the East African Rift System is the result of the actions of numerous normal faults (Haidutov 1976; Kearey et al. 2009; Graniczny et al. 2011). Other notable geographic features are Lake Victoria, Lake Nyasa and Lake Tanganyika that belong to the Great African Lakes formed as an outcome of the geologic evolution, including complex tectonic movements.

The tectonic history of the Northeast African–Arabian plate reveals formation of the passive margins of the Paleotethys and the Neotethys (Guiraud and Bosworth 1999). A system of Tanzanian–Kenyan rifts was created as a result of the tectonic crustal extension during the Mesozoic and early Tertiary, with the Central African Rift System being formed in the Late Jurassic (Bosworth 1992; Bosworth and Maurin 1993; Scoon 2018). Nowadays, the Central African Rift System stretches from central Sudan to southern Kenya and includes Tanzania.

Tanzania is significant for a wide variety of landscapes: 1) raised beaches and marine-cut platforms; 2) river terraces, valley bottoms; 3) coastal wetlands, beaches and lagoons formed by waves and tidal impact

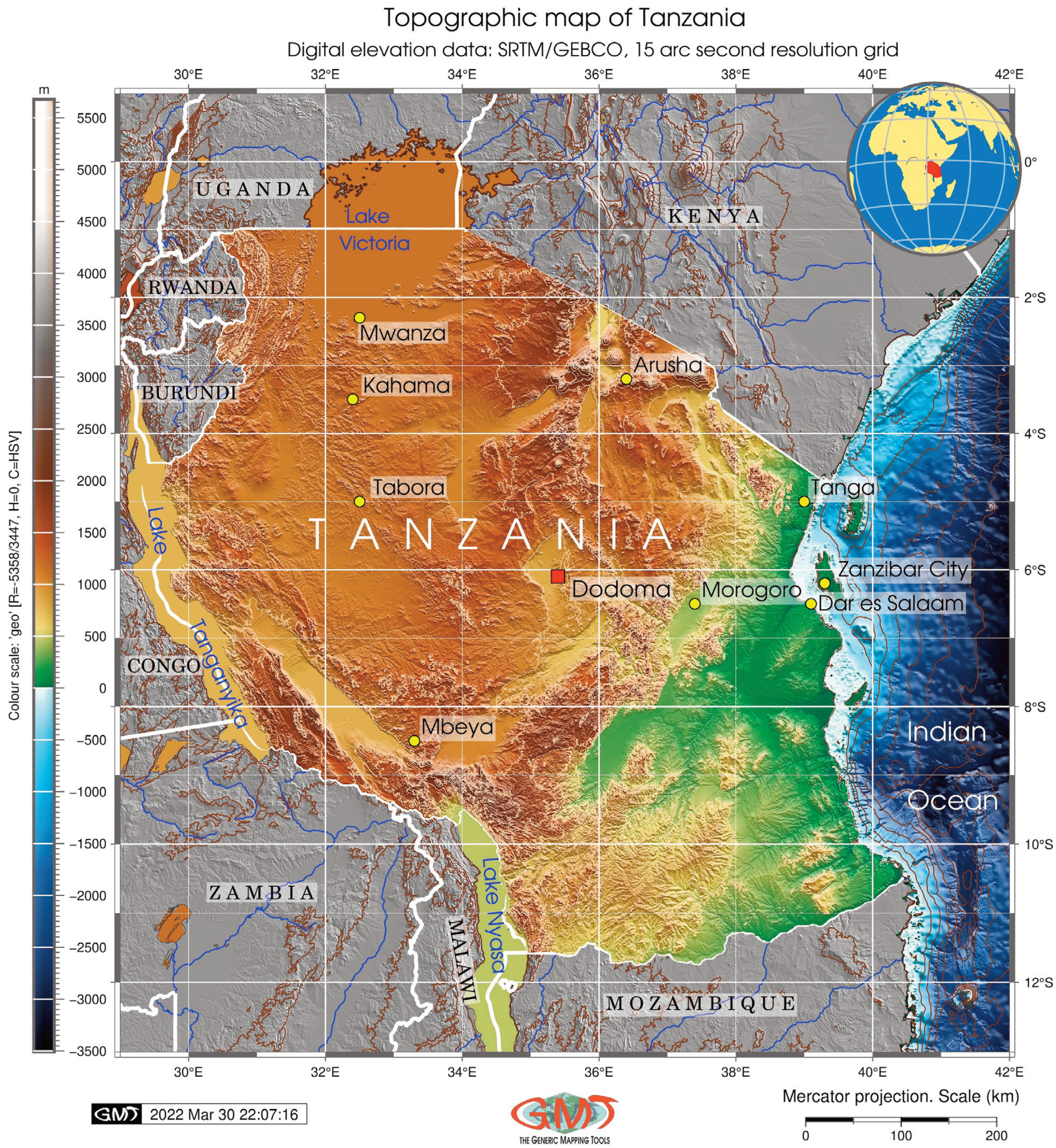

Fig. 1. Topographic map of Tanzania. Data: General Bathymetric Chart of the Oceans (GEBCO) overprinted on the monochrome shadow Digital Elevation Model (DEM) image. Data source: GEBCO Compilation Group 2020. Map source: elaborated by the author.

in the eastern coasts of Tanzania; 4) mudflats, marshes, mangrove swamps, estuaries and deltas having tidal origin; 5) rift system depressions characterized by salt lakes, playas, swamps, wetlands and streams; 6) mountainous highlands; 7) lakes, swamps and floodplains (Cooke 1974). The variability of these landscapes was created in the course of the geologic evolution and shaped by external factors, such as aeolian processes, hydrological networks, soil processes including erosion and vegetation coverage.

Mapping such a diverse region, rich in geological resources and natural landscapes, requires advanced cartographic approaches and robust geospatial data. In response to these needs, this study brings together multi-source datasets, advanced scripting and GIS methods. Investigating the links between the geologic and topographic settings can provide new information derived from the geospatial data. The objective of the work is to present an advanced cartographic approach of the integrated data analysis. The study aims to highlight the correlations between the geologic and geophysical settings of Tanzania and its relief as reflected in regional geomorphology. The practical goal is to fill in the gap between the modern cartographic solutions and the existing geological and geophysical datasets.

Nowadays, in the epoch of automatization, the development of scripting in cartography has become a topic of critical importance. Methods of applied programming have attracted great interest due to their broad potential and an increasing need for automated mapping (Schenke and Lemenkova 2008; Koskinen et al. 2019; Lemenkova 2019a, 2021b; Höhle 2021). Another important question of modern cartography concerns availability of data and methods. Some commercial GIS applications have restricted access and are not available to all users. While these software solutions provide base tools for mapping, it is always advisable to use open source GIS and data to enable repeatability of research. This study presents cartographic methods which can be benchmarked in similar studies. Moreover, using the proposed workflow, other high-resolution datasets can be employed for cross evaluations and expanding research goals.

Background information on the cartographic data on Tanzania has revealed the lack of scripting approaches (Berry and Hellen 1972; Bosworth and Strecker 1997; Delvaux 2001; Collins et al. 2004; Fritz et al. 2005). Scripting is, nevertheless, a useful technique enabling to repeat workflow, shorten time and increase automation of data processing. While closely related in spatial data processing, GIS and scripting cartography are not the same. Scripting performs mapping by running the script which consists of command lines of codes written using programming syntax. Traditional GIS mapping is largely a Graphical User Interface (GUI)-based process. The workflow of this study involved making decisions on map design, organizing layers across the range of the supported formats, preparing the layout, with the primary goal of maintaining map aesthetics and readability. This study answers the following two questions: (1) how scripting and GIS can be used in integrated mapping; (2) what information can be derived from thematic data to get better insights into the regional setting of Tanzania.

MATERIALS AND METHODS

Data

The presented geospatial data analysis consists in abstracting the diverse datasets available online. These data have been integrated into a project on Tanzania and targeted for representation. The topographic data (Fig. 1) were based on GEBCO (GEBCO Compilation Group 2020); the geological dataset (Fig. 2) was retrieved from the United States Geological Survey (USGS) (Persits et al. 1997; Pollastro et al. 1999). Other existing geological datasets include traditional maps (Pinna et al. 1996, 2000; BRGM et al. 2004; Kabete et al. 2012B; Quennell, 1956; Quennell et al. 1956). Besides the geological data available on Tanzania, there is online mapping coverage on relevant resources (Geological Survey of Tansania 2021). The 3D model (Fig. 3) was based on the ETOPO1 (Amante and Eakins 2009); the geoid map (Fig. 4) on the EGM-2008 (Pavlis et al. 2012); the geophysical data (Fig. 5) were derived from the gravity grids (Sandwell and Smith 1997; Sandwell et al. 2014), the DEM was obtained from the R ‘raster’ package (Hijmans and van Etten 2012), Figs 6–9.

Using GEBCO for topographic mapping is reported in literature (Masalu 2008; Lindh and Lemenkova 2021; Gauger et al. 2007; Lemenkova 2019c, 2020e, 2021d, 2021e). Its popularity can be explained by its availability (https://www.gebco.net/) and unprecedentedly high resolution. Land areas of GEBCO are based on the SRTM (Farr and Kobrick 2000; Farr et al. 2007; NASA Shuttle Radar Topography Mission (SRTM) 2013).

Scripting in GMT

Generic Mapping Tools (GMT) is an advanced scripting toolset (Wessel et al. 2019), which presents an automated suite of modules for cartographic data processing and design techniques using GMT syntax, as demonstrated earlier (Lemenkova 2020a, 2021a). GMT presents a promising scripting approach in cartography. Originally developed for geophysical needs, it has gained significance for thematic mapping (Lemenkova 2019b; 2019d). GMT applies shell scripts for cartographic visualization, seeking to create artistic, print quality 2D and 3D maps using modules for data processing. GMT discriminates commands and flags in a script and plots a map by executing this script. The commands are written by means of modules. The maps demonstrated in Figs 1, 4 and 5 were made applying the modules ‘grdimage’, ‘pscoast’, ‘grdcontour’, ‘psbasemap’, ‘pstext’, ‘psxy’ and ‘psclip’. The GMT scripts used for mapping in Figs 1, 3, 4 and 5 are provided in the Appendix. For example, the following GMT modules were used for visualization of

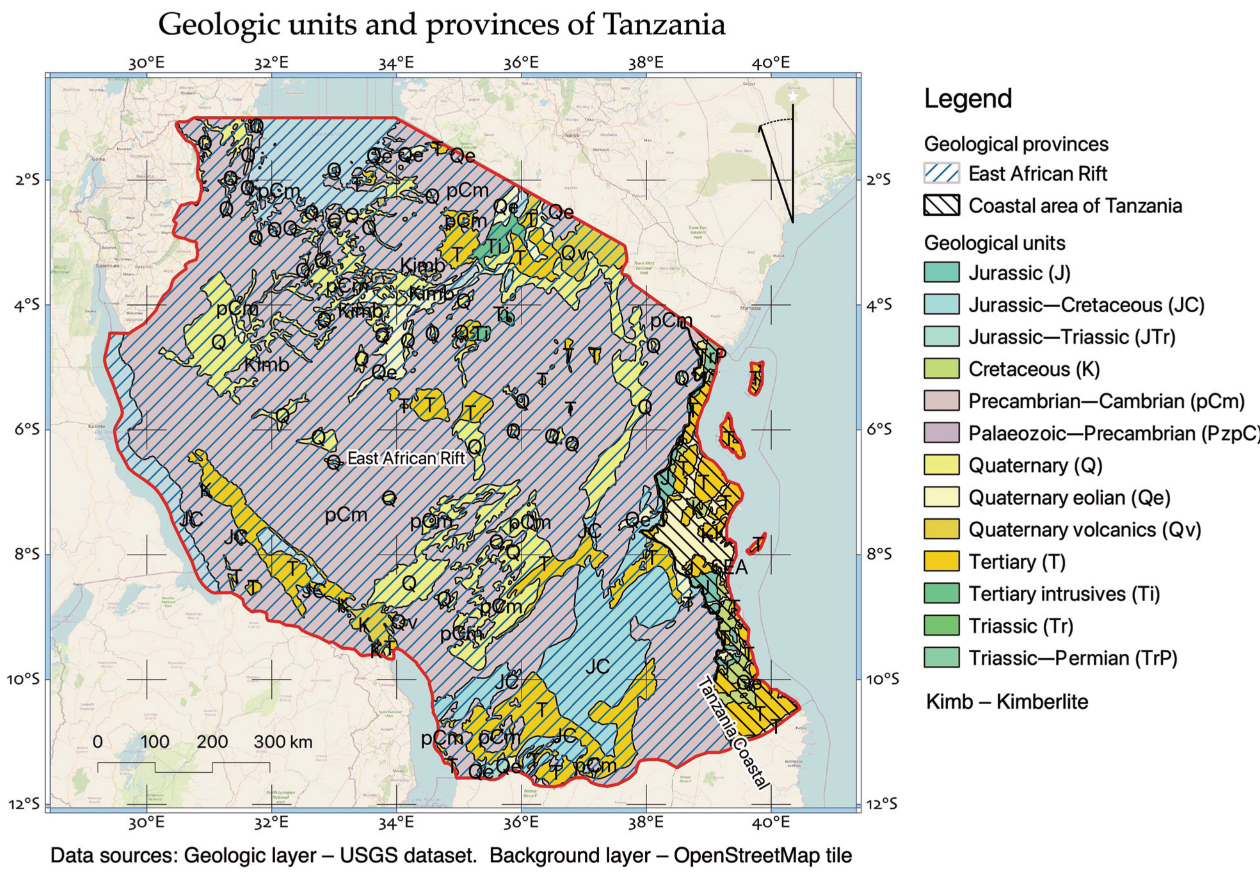

Fig. 2. Geological units and provinces in Tanzania. Data source: United States Geological Survey (USGS) (Persits et al. 1997) and OpenStreetMap (OpenStreetMap contributors). Map source: elaborated by the author.

the cartographic elements: the ‘grdimage’ module for plotting raster image, ‘pscoast’ for adding linear objects (coastal lines, country borders and rivers), ‘grdcontour’ for plotting isolines, ‘psbasemap’ for adding cartographic elements (legend, title, subtitle, background, grid, scale bar, north arrow, and graticule ticks), ‘pstext’ for plotting texts, ‘psclip’ for clipping the area (script 1 in Appendix), and ‘grdview’ for 3D. The legend was added by ‘psscale’ (scripts 1–4 in Appendix). Thus, each module was utilized for a specific purpose in a workflow. Colour palettes used in the makecpt module aimed to enhance data appearance. For example, Fig. 4 was plotted by the ‘wysiwig’ palette and Fig. 5 by ‘haxby’. Figure 1 shows a clipped area by the ‘geo’ palette overlain by the monochrome SRTM (Farr and Kobrick 2000; Farr et al. 2007). The 3D mapping is presented in Fig. 3 as a perspective overlay of the 3D mesh grid on ETOPO5 (5-m grid) over the 2D topographic contour based on ETOPO1 (script 2 in Appendix). Likewise, cartographic elements were plotted by various modules (see scripts 3 and 4 in Appendix). In such a way, the modules of GMT describe and control the appearance of the elements by adjusted flags within the executed module. A conceptual approach of scripting consists in selecting modules based on functionality. It increases the speed and precision of the machine’s performance and results in print-quality maps with layouts where the appearance of each cartographic element is regulated in a refined and detailed way.

Mapping in QGIS

QGIS presents a classic software that enables to visualize spatial information using a GUI. The map of geological units and provinces of Tanzania (Fig. 2) was plotted in QGIS (QGIS.ORG Association 2021) by employing the existing methods (Lemenkova 2020b, 2020c).

Visualization in QGIS requires taking the following decisions in a workflow: (1) how and from where the data are collected (data capture); (2) the extent and resolution of the data (data quality); (3) how data layers are displayed (data organization); (4) how the layout is organized and where the cartographic elements are placed (legend, scale

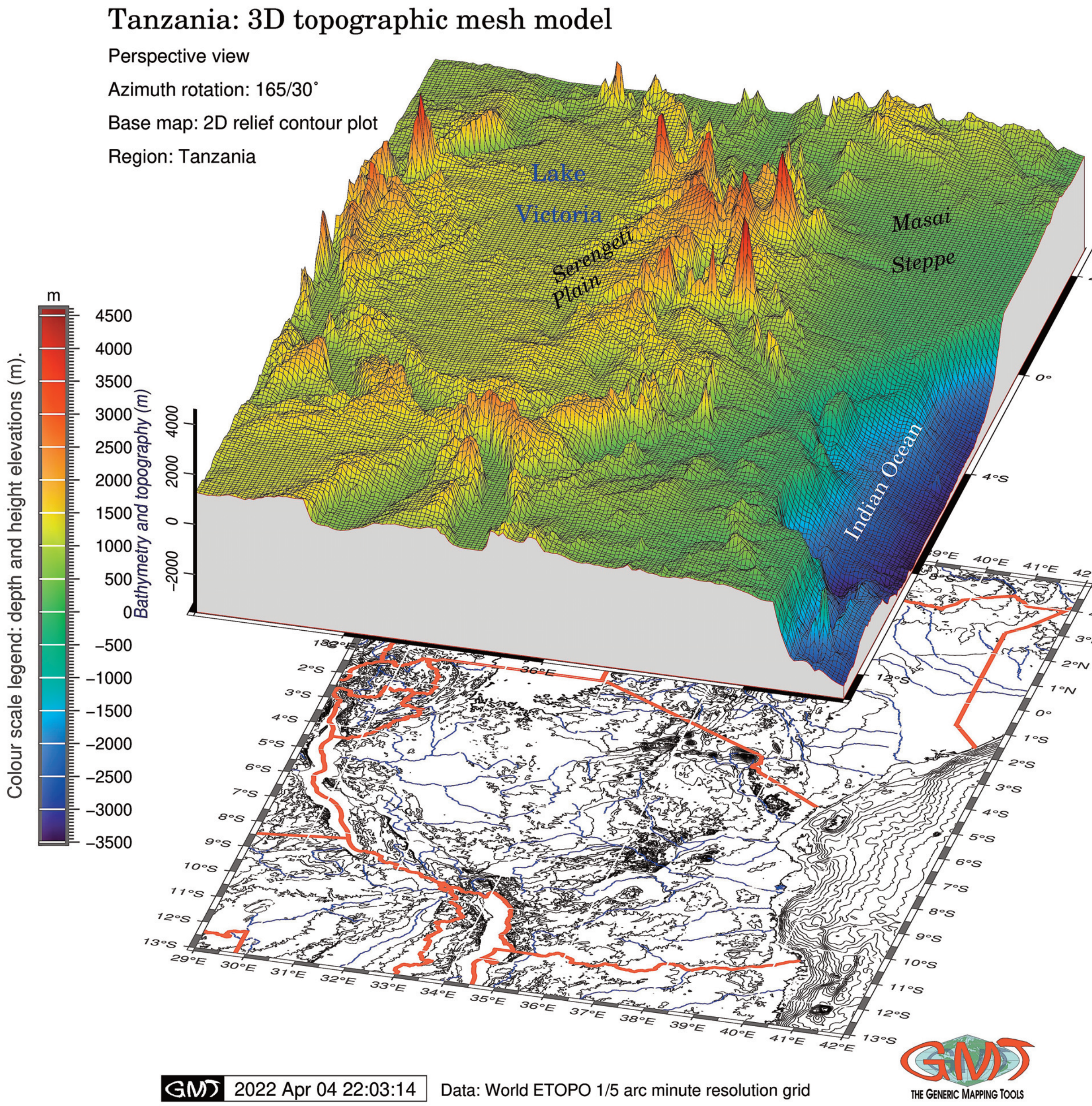

Fig. 3. 3D model of Tanzania. Data source: ETOPO1 5-minute resolution grid (Amante and Eakins 2009). Vertical exaggeration of z-axis scale is 3.5 (z-axis scaling as -JZ3.5c in the ʿgrdviewʾ module of GMT). Horizontal resolution is 1:10,000,000. Map source: elaborated by the author.

bar, annotations, map, north arrow) (data visualization and representation); (5) which requirements are given for symbolizing the content. These steps were performed as a workflow in QGIS to achieve effective mapping (Fig. 2). As a result, an updated geological map was created which shows geological units and provinces of Tanzania using USGS data (Pollastro et al. 1999), with the cartographic elements illustrated by means of open geospatial data from QGIS.

Programming in R

The data processing was technically carried out using RStudio (RStudio Team 2017) of R language (R Core Team 2021). The R-based geomorphometric mapping presents a series of maps (Figs 6, 7, 8 and 9) describing the fundamental parameters of the relief: slope, aspect, hillshade and elevation heights. Here the maps were created on the basis of the Digital Elevation Model (DEM)

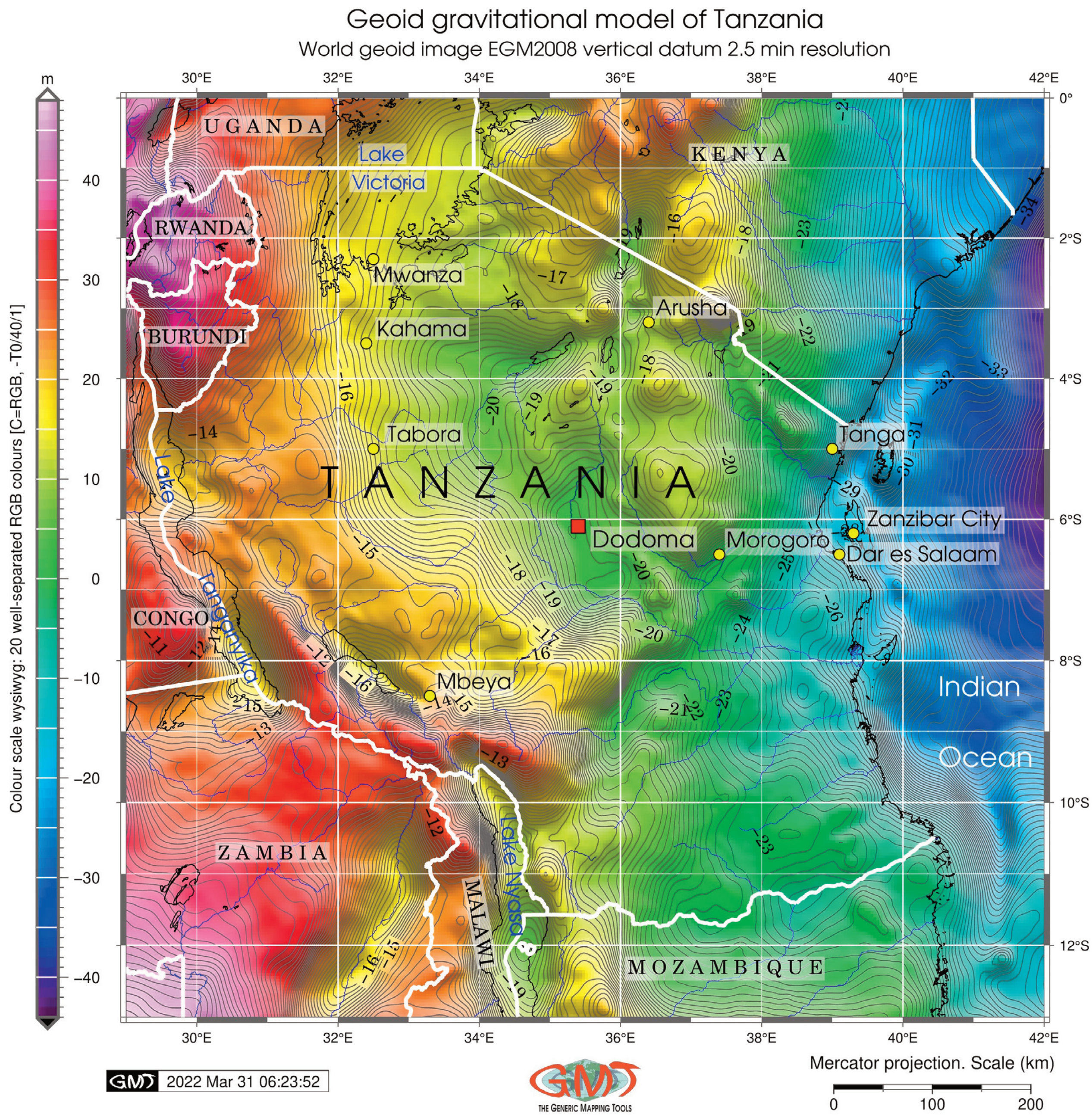

Fig. 4. Geoid gravitational model of Tanzania. Data: EGM-2008. Map source: elaborated by the author.

where slope, aspect, hillshade and elevation heights are, in turn, derivatives used for geomorphological analyses. Data capture was performed by ‘getData’ function of the ‘raster’ package. Modelling of slope, aspect, hillshade and elevation was performed by the ‘raster’ package.

The cartographic adjustments of the maps were made by the ‘tmap’ package of R, which improved the visual appearance of the maps (Figs 6–9) by changing style, positioning, colour and fonts of the cartographic elements modified according to map layouts. The colour palettes were selected from the ‘RColorBrewer’ package using RGB (Red, Green, Blue) and CMYK (Cyan, Magenta, Yellow, Black) palettes for the maps in Figs 6–9 (Brewer et al. 2003; Brewer 2003; Harrower and Brewer 2003). The ‘tmap’ package of R (Tennekes 2018) designed for generating maps employs the scripting approach based on the R syntax (Lemenkova 2020d) rather than the traditional GIS (e.g. Suetova et al. 2005; Lemenkova 2011, 2021c, 2021f; Klaučo et al. 2014, 2017). The R script used for plotting Figs 6–9 is provided in the

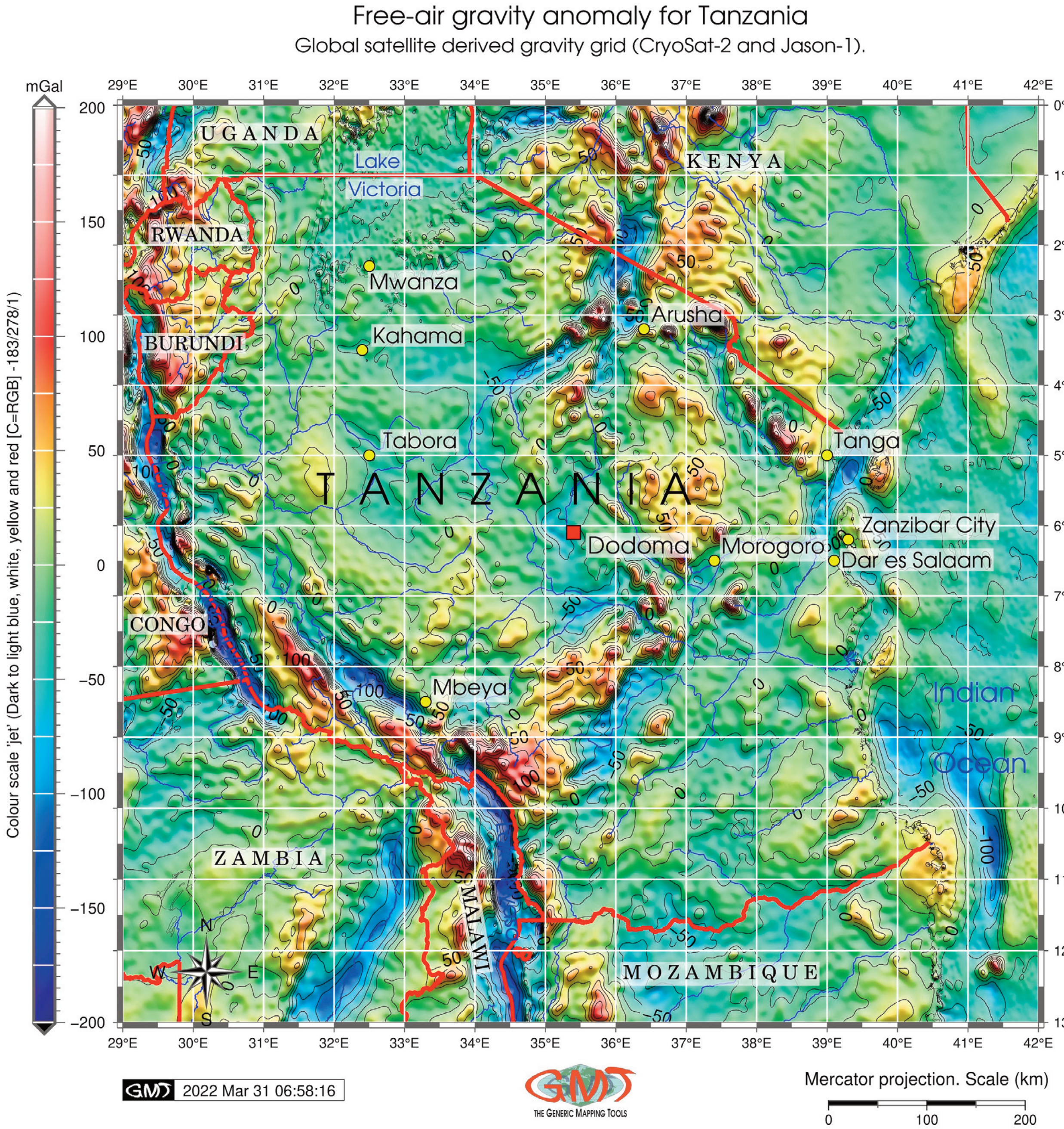

Fig. 5. Free-air gravity anomaly of Tanzania. Data source: CryoSat-2 and Jason-1. Map source: elaborated by the author.

Appendix for more technical details. The lines of the script control the annotation styles, fonts, angle of graticule, layout style and other cartographic adjustments (Figs 6–9).

RESULTS

The advanced cartographic approaches have generated nine new maps aimed to visualize Tanzania in multiple thematic content: geophysics, geodesy, geology, topography and geomorphology. According to the data inspection by GDAL (Geospatial Data Abstraction Library), the topography reaches up to 5677 m with the mean of 617 m, which also includes the coastal area of the Indian Ocean with the minimal values at –3510 m (Fig. 1). The inspection was carried out using the command "gdalinfo -stats tz_relief.nc", which checked the values of the cells in the file. In GDAL the "gdalinfo" runs the

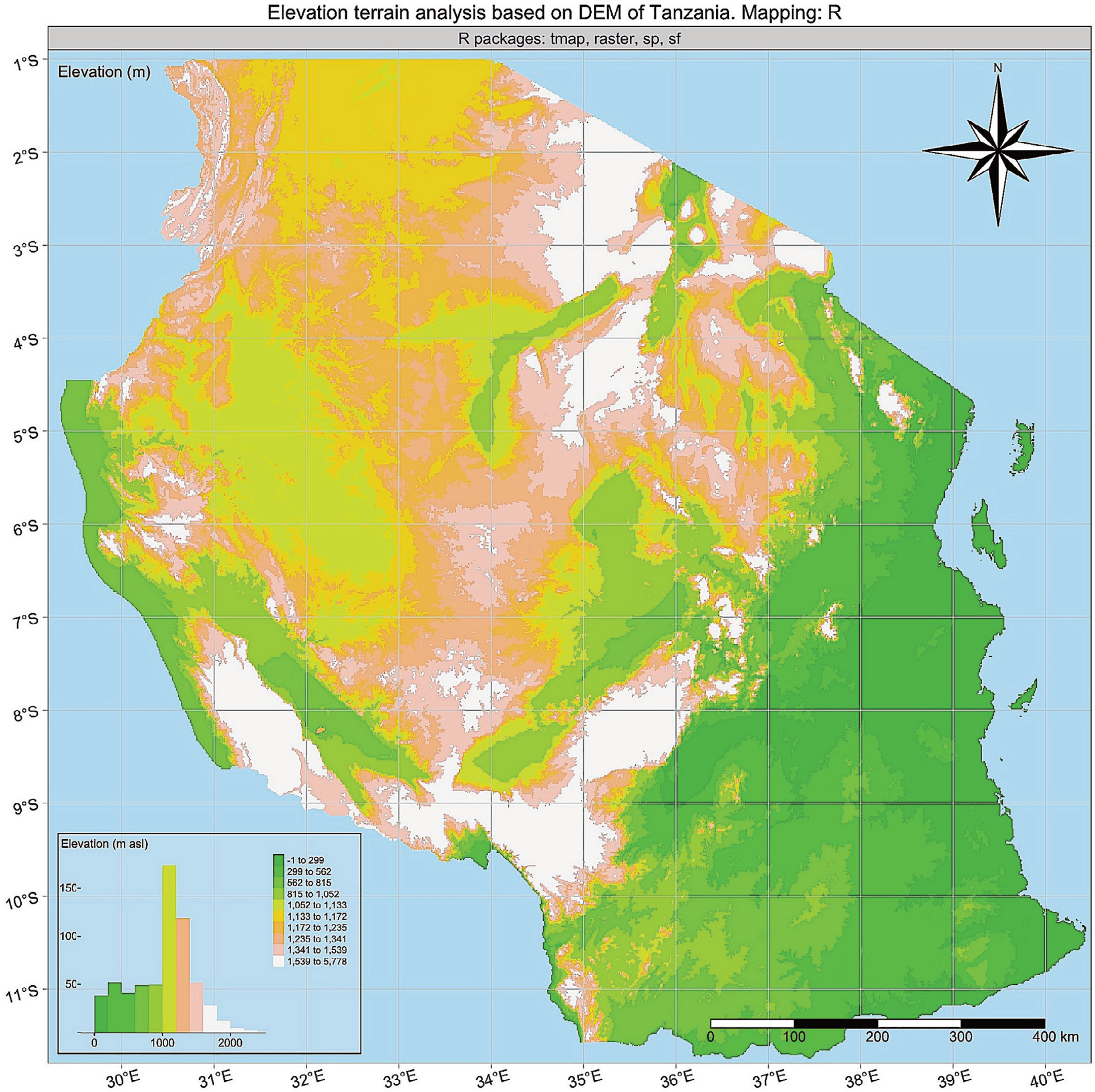

Fig. 6. Visualization of the Digital Elevation Model (DEM) of the terrain of Tanzania. Mapping by R using packages 'tmap', 'raster', 'sp', 'sf'. Map source: elaborated by the author.

command in a console, the "-stats" flag means the statistics command and the "tz_relief.nc" is the name of the file in NetCDF format. The oceanic area includes the coastal region of Tanzania (Fig. 1).

Figure 2 shows the geologic content prepared by means of QGIS. The Precambrian to Cambrian (pCm) geological unit is located within the East African Rift. The other widely distributed types include Quaternary (Q) deposits and Quaternary volcanics (Qv) in the north. The Tertiary (T) outcrops are found occasionally, lying mostly along the coastal area as well as in southern and western regions. The Jurassic to Cretaceous (JC) units are mainly located in the south (Fig. 2). Compared to the existing 3D mapping of Eastern Africa (Bosworth 1994) which visualizes graben geometry as graphics, the 3D map shows an elevation perspective view made by the 'grdview' module featuring major objects: Lake Victoria, the Masai Steppe, the Serengeti Plain (Fig. 3).

The 3D map (Fig. 3) was created by scripting which provides a time-efficient workflow for accurate data

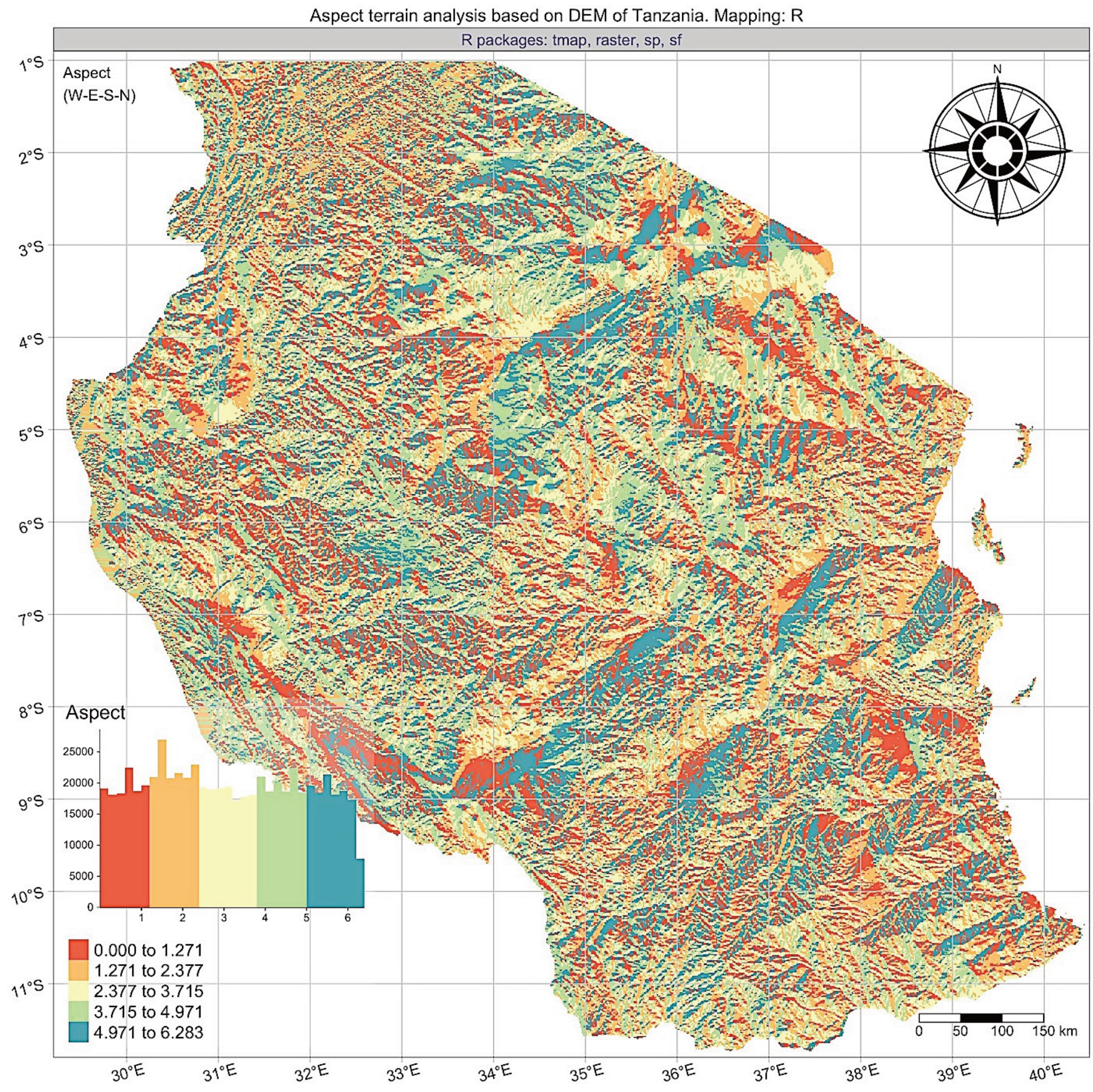

Fig. 7. Aspect terrain visualization based on DEM of Tanzania. Mapping by R using packages 'tmap', 'raster', 'sp', 'sf'. Map source: elaborated by the author.

visualization using a high degree of automation. This is achieved by the automated map plotting algorithms employing stepwise modular scripting techniques aimed to present updated information on the topography of Tanzania.

Figures 4 and 5 show the geoid and free-air gravity anomaly in Tanzania. The maximum range of geoid undulations (Fig. 4) reaches 48 mGal (Burundi, Rwanda and NE Zambia), while the minimum is –45 mGal, pointing to variations in the rock density causing transformation in the geoid values. The analysis of Fig. 5 indicates variations in the free-air gravity anomalies with the dominant values of 45/+25 mGal (Fig. 5). Accurate detection of geoid and gravity values enables to compare variations in the regional geophysical setting through precise visualization by GMT. In this way, mapping based on the geoid Earth Gravitational Model 2008 (EGM-2008) creates a platform for further geophysical analysis. Scripting algorithms of raster data processing enable to plot maps accurately due to the automated workflow. This makes it possible to detect correlations among the geophysical and geologic variables by the comparison of maps. The geological and geophysical maps, compared to

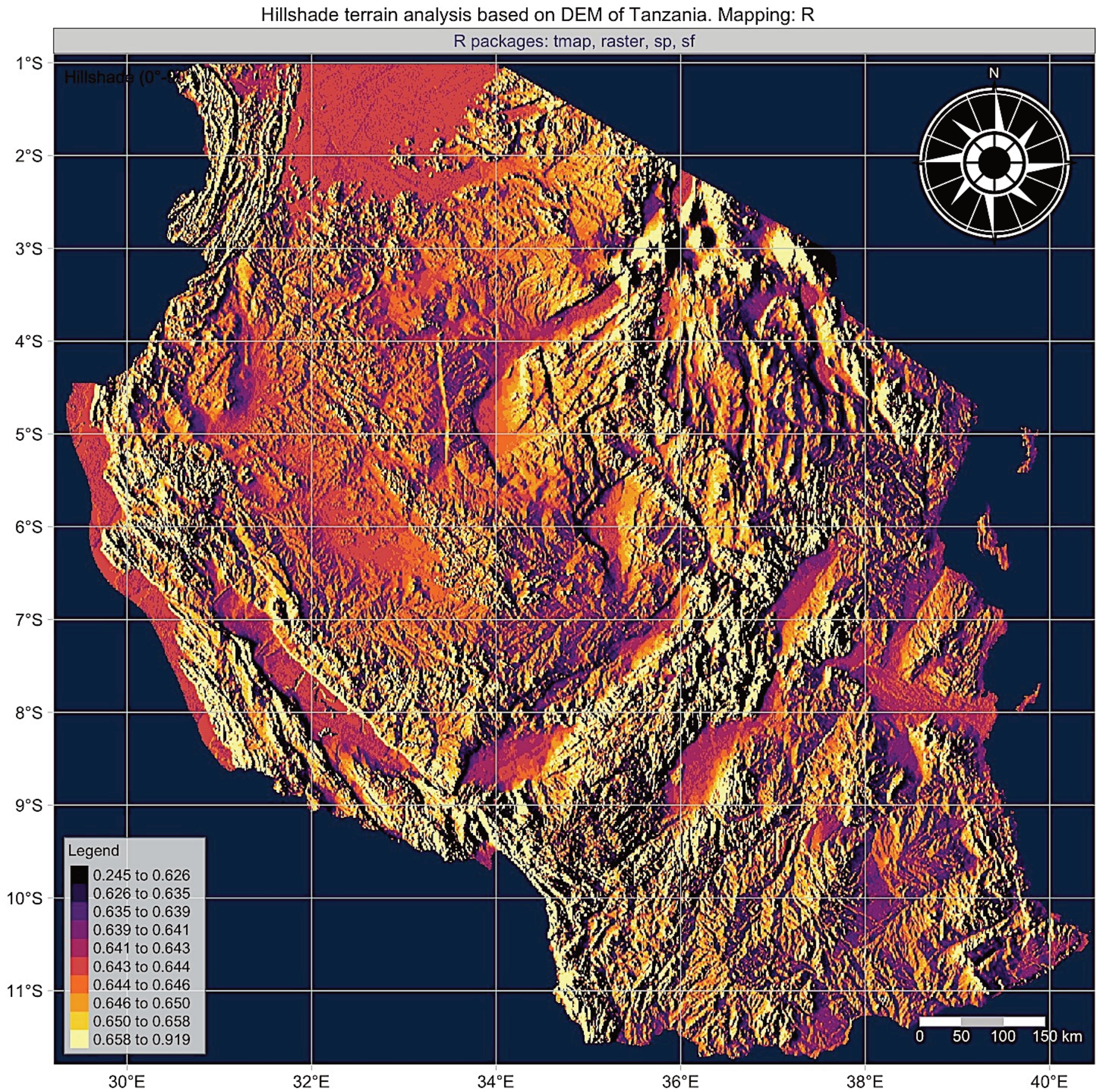

Fig. 8. Hillshade terrain visualization based on DEM of Tanzania. Mapping by R using packages 'tmap', 'raster', 'sp', 'sf'. Map source: elaborated by the author.

the geomorphology, help to reveal impact factors contributing to the relief formation reflected in the local and regional landforms, depression and mountains.

The series of maps in Figs 6–9 reveal variations in the geomorphometric parameters. Aspect orientation by compass is modelled in Fig. 7 based on the DEM shown in Fig. 6. The hillshade is visualized in Fig. 8 and slope steepness in Fig. 9, showing the variability of the relief in Tanzania based on the DEM (Fig. 6). The comparison of these maps refers to the connection with the geomorphology formed as a result of geologic evolution. This enables to gain new insights into the Earth observation data. The response of the local topography of Tanzania to external effects, such as river network, soil erosion and vegetation coverage, may become an extension of this research using additional large-scale datasets.

A series of geomorphometric analytical maps was plotted to show the variability of the relief in the country. The variety of the landforms of Tanzania can be studied in detail resorting to morphometric characteristics (slope

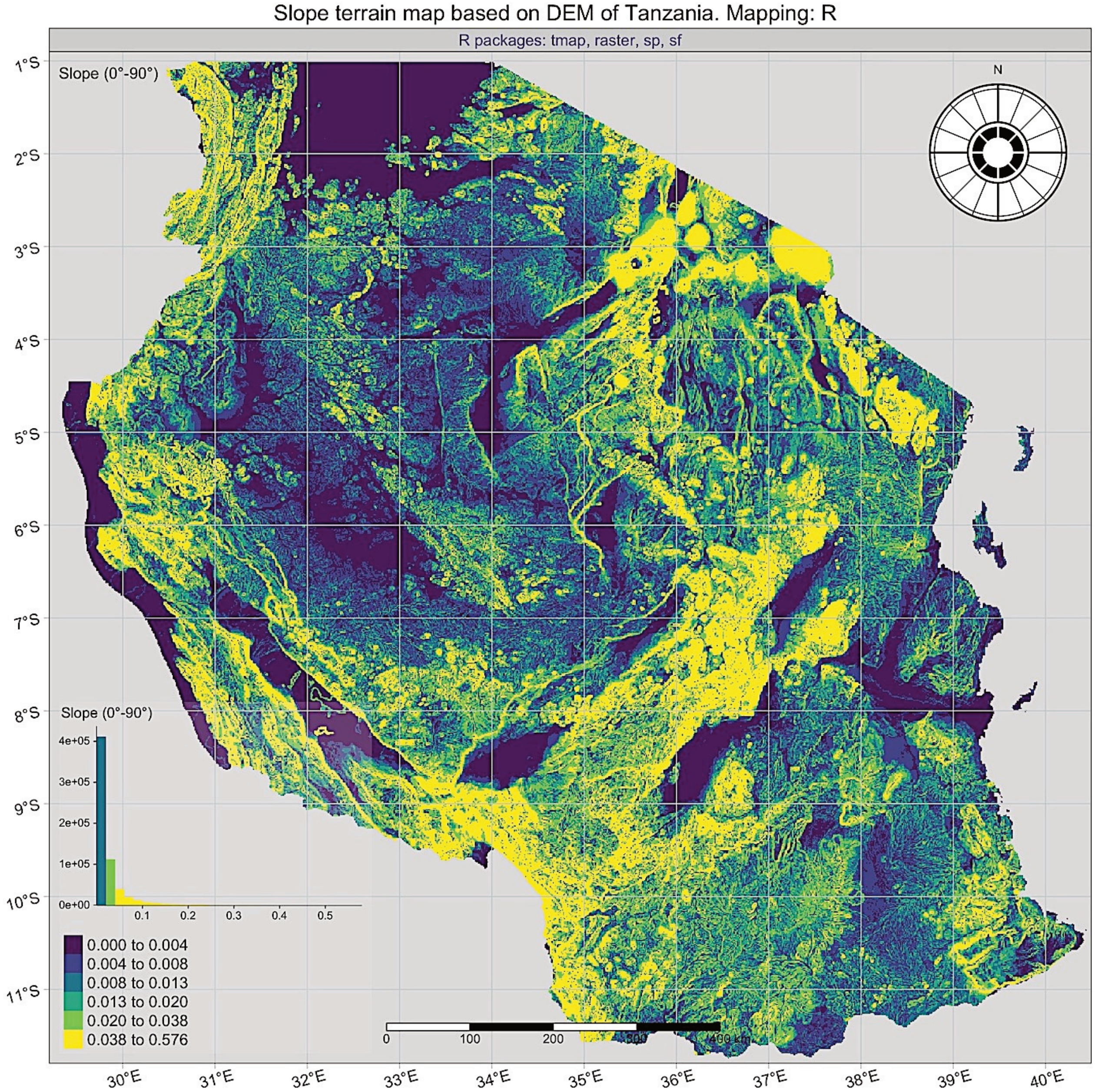

Fig. 9. Slope terrain visualization based on DEM of Tanzania. Mapping by R using packages 'tmap', 'raster', 'sp', 'sf'. Map source: elaborated by the author.

in Fig. 9, aspect in Fig. 7, elevations based on the DEM in Fig. 6, hillshade in Fig. 8). The geomorphology can be explored and better analysed using geological and geophysical maps employed as benchmarks because the depressions and elevations (mountain regions) correspond to the major geologic and tectonic features: the Great Rift Valley, the Great Lakes. In turn, landscape forms such as the Masai Steppe or the Serengeti Plain follow general geomorphic structures of the Earth with corresponding types of soil and vegetation.

DISCUSSION

Automatization is a continuous challenge in modern cartography (Msabi and Makonyo 2021; Klaučo et al. 2013a, 2013b; Muthoni et al. 2020). The importance of the effective mapping for environmental and geologic science is shown in relevant literature (Alphayo and Sharma 2018; Kempen et al. 2019; Ijumulana et al. 2020; Armadillo et al. 2020). Automated cartographic methods are demonstrated in this paper by scripting languages

GMT and R used for console-based mapping of Tanzania. The contribution of this study to the Earth science consists in increasing geo-information by presenting nine new maps of Tanzania.

With diverse performance of the cartographic tools and graphical analysis of data visualization, the results reveal that there is a correspondence between the geologic setting, geophysical anomalies and relief of Tanzania. The results show that both the shell script and GIS can be effectively used in cartography for comparative analysis of a regional setting retrieving data from geological, geophysical, geodetic, geomorphologic and topographic sources. A novel cartographic technique integrating GMT, QGIS and R is particularly useful in the analysis of maps that can be interpreted independently or comparatively. Unlike the traditional GIS, scripting functions are similar to programming with the possibility of reusing. Therefore, scripts can be repeated in similar studies in order to increase the speed and accuracy of mapping.

Comparable approaches for mapping Tanzania include examples of the traditional mapping. In fact, the majority of the existing maps of Tanzania use ArcGIS or QGIS (e.g. Schweikart et al. 2014; Nijbroek and Andelman 2016; Koskikala et al. 2020; Mseli et al. 2021). This is mostly explained by the relative simplicity of the traditional GIS. However, compared to GMT, limited functionality of GIS does not enable plotting maps in a fast and automated way, not to mention the print-quality graphics and design. This work continued the studies on Tanzania in the cartographic domain by incorporating the latest geophysical and geological datasets and advanced scripting. Thus, it is an advantage in further cartographic development enabling to link the geomorphological and geophysical data to better analyse the regional setting of Tanzania. The weak point of this approach might be that GMT is relatively difficult to master compared to the traditional GIS methods.

The presented maps may serve for the benefit of geospatial and geologic monitoring in Tanzania on local, regional and national scales. An integrated mapping can be applied for environmental monitoring of the national parks or as modelling in geologic prospecting. Further applications can include natural resource management, mineral resource exploration, data visualization and interpretation. A multi-scale approach comprises small-scale geophysical data, high-resolution topographic data and a medium-scale DEM by R. The cartographic focus on resolution reflects the need for the integration of multi-source data that may be of various origins and vary in precision. The geomorphological mapping aims to gain better insights into the landscapes reflected in the topography of Tanzania and into the corresponding major tectonic features, i.e. the East African Rift and the Great Lakes.

CONCLUSIONS

This study has referred to two approaches of mapping: scripting and traditional methods. Its aim was to improve the existing cartographic methods towards more automated, accurate and fast workflows, achieved through scripting. In addition, a review on the geology and the environmental setting of Tanzania was carried out to analyse the geologic structure influencing the geomorphology of the country, formed by complex tectonic processes (Harpum 1970; Mwanukuzi 2008, 2009, 2011; Miller and Doyle 2014). Geologic information was considered to link the geologic and geomorphological processes expressed in relief.

The thematic overlay of several maps (geophysics, geomorphology, topography and geology) aimed to support correlations between the geologic, topographic and geophysical phenomena in the country, i.e. the East African Rift System, Lake Victoria, Lake Tanganyika and Lake Nyasa, the Serengeti Plain and the Masai Steppe. For example, a correspondence exists between the extent of the rifts, topographic heights and directions of the geological units. Anomalies in geophysical fields reflect gravity fluctuations which well correspond with the topographic depressions. Slope steepness, aspect and actual relief representation were compared with the 2D and 3D models. The presented methods of mapping have facilitated map interpretation and analysis: for the vector maps in QGIS, raster maps in GMT and numerical modelling in R.

The actuality of this study can be summarized in four ways: (1) new maps based on the high-resolution data contribute to an increase in information on Tanzania; (2) scripting approaches can serve as a guide for similar workflows; (3) maps made using open data sources can be reused in similar studies on Tanzania; (4) the possibility of combining various thematic layers can support the future research and thus the understanding regarding the geologic formation and geomorphology in the context of tectonic processes. It is recommended that a comparative analysis of various data (projections, data extent, vector and raster formats) be applied for further extended research. This paper has presented a combination of scripting and traditional methods for mapping Tanzania with the results referred to as a practical framework for organizing similar thematic projects.

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Appendix

1. GMT script used for plotting Fig. 1: Topographic map of Tanzania.

```
ps=Topo_TZ.ps
gmt grdimage tz_relief.nc -Cocean.cpt -R29/42/-13/1 -JM6.5i -I+a15+ne0.75 -Xc -P -K > $ps
gmt pscoast -R -J -ETZ -Gc -O -K >> $ps
echo "-10000 150 10000 150" > gray.cpt
gmt grdgradient tz_relief.nc -Nt1 -A45 -Gtanzania_topo_i.nc
gmt grdimage tz_relief.nc -Itanzania_topo_i.nc -J -Cgray.cpt -O -K >> $ps
gmt grdcontour tz_relief.nc -R -J -C500 -Wthinnest,dimgray -O -K >> $ps
gmt pscoast -R -J -O -K -Q >> $ps
gmt grdcontour tz_relief.nc -R -J -C500 -Wthinner,darkbrown -O -K >> $ps
gmt pscoast -R -J -P -Ia/thinner,blue -Na -N1/thickest,white -W0.1p -Df -O -K >> $ps
gmt psclip -JM -R tanzania.txt -O -K >> $ps
gmt grdimage tz_relief.nc -Cocean.cpt -R29/42/-13/1 -JM6.5i -I+a15+ne0.75 -Xc -P -O -K >> $ps
gmt grdcontour tz_relief.nc -R -J -C500 -Wthinnest,navajowhite1 -O -K >> $ps
gmt pscoast -R -J -P -Ia/thinner,blue -Na -N1/thickest,khaki1 -W0.1p -Df -O -K >> $ps
gmt psclip -C -O -K >> $ps
gmt psscale -Dg27.5/-13.0+w17.7c/0.15i+v+o0.3/0i+ml -R -J -Cocean.cpt \
  -Bg500f50a500+l"Color scale: 'geo' [R=-5358/3447, H=0, C=HSV]" -I0.2 -By+lm -O -K >> $ps
gmt psbasemap -R -J -Bpxg4f1a2 -Bpyg2f1a2 -Bsxg2 -Bsyg1 \
        -B+t"Topographic map of Tanzania" -O -K >> $ps
gmt psbasemap -R -J \
  -Lx14.5c/-1.3c+c50+w200k+l"Mercator projection. Scale (km)"+f -UBL/-15p/-38p -O -K >> $ps
gmt pstext -R -J -N -O -K -F+f10p,13,black+jLB -Gwhite@50 >> $ps << EOF
39.5 -6.1 Zanzibar City EOF
gmt psbasemap -R -J -O -K -DjTR+w3.2c+o-0.2c/-0.2c+stmp >> $ps
read x0 y0 w h < tmp
gmt pscoast -Rg -JG35.0/-6.0N/$w -Da -Glightgoldenrod1 -A5000 \
        -Bga -Wfaint -ETZ+gred -Sdodgerblue -O -K -X$x0 -Y$y0 >> $ps
gmt psxy -R -J -O -K -T  -X-${x0} -Y-${y0}
>> $ps
gmt logo -Dx7.0/-2.0+o0.1i/0.1i+w2c -O -K >> $ps
gmt pstext -R0/10/0/15 -JX10/10 -X0.1c -Y12.5c -N -O -F+f10p,13,black+jLB >> $ps << EOF
3.0 9.0 Digital elevation data: SRTM/GEBCO, 15 arc sec resolution grid EOF
gmt psconvert Topo_TZ.ps -A1.5c -E720 -Tj -Z
```

2. GMT script used for plotting Fig. 3: 3D model of Tanzania.

```
gmt grdcut earth_relief_05m.grd -R29/42/-13/5 -Gtz_relief5.nc
gdalinfo -stats tz_relief5.nc
gmt makecpt -Cturbo.cpt -V -T-3527/4621 > myocean.cpt
ps=TZ_3D.ps
gmt grdcontour ETOPO1_Ice_g_gmt4.grd -JM10c -R29/42/-13/5 -p165/30 -C250 -Gd3c -Y3c \
        -U/-0.5c/-1c/"Data: World ETOPO 1/5 arc minute resolution grid" -P -K > $ps
gmt pscoast -R -J -p165/30 -P -Ia/thinner,blue \
        -Bpxg2f0.5a1 -Bpyg2f0.5a1 -Bsxg2 -Bsyg1 -Na -N1/thickest,tomato -W0.1p -Df -O -K >> $ps
gmt psscale -Dg26.0/-10+w8.0c/0.4c+v+o0.0/0.5c+ml -R -J -Cmyocean.cpt -Bg500f50a500+l"Color scale legend: depth
and height elevations (m)." -I0.2 -By+lm -O -K >> $ps
gmt grdview tz_relief5.nc -J -R -JZ3.5c -Cmyocean.cpt -p165/30 -Qsm -N-3500+glightgray -Wm0.07p -Wf0.1p,red -
B4/4/2000:"Bathymetry and topography (m)":ESwZ -S5 -Y5.0c -O -K >> $ps
gmt pstext -R -J -N -O -K \
-F+jTL+f9p,25,white+jLB+a-300 >> $ps << EOF
```

```
41.8 -10.0 Indian Ocean EOF
gmt pstext -R -J -N -O -K \
-F+jTL+f9p,26,black+jLB+a-350 >> $ps << EOF
42.5 -4.0 Masai
42.5 -4.8 Steppe EOF
gmt logo -Dx10.5/-5.5+o0.0c/-0.5c+w2c -O -K >> $ps
gmt pstext -R0/10/0/10 -Jx1 -X-0.8c -Y0.0c -N -O -K \
-F+f12p,25,black+jLB >> $ps << EOF
-0.5 10.0 Tanzania: 3D Topographic Mesh Model
EOF
gmt pstext -R0/10/0/10 -Jx1 -X0.0c -Y0.0c -N -O\
   -F+f8p,0,black+jLB >> $ps << EOF
-0.5 9.5 Perspective view
-0.5 9.0 Azimuth rotation: 165/30\232
-0.5 8.5 Base map: 2D relief contour plot
-0.5 8.0 Region: Tanzania
EOF
gmt psconvert TZ_3D.ps -A1.2c -E720 -Tj -P -Z
```

3. GMT script used for plotting Fig. 4: Geoid gravitational model of Tanzania.

```
gmt grdconvert s45e00/w001001.adf geoid_TZ.grd
gdalinfo geoid_TZ.grd -stats
gmt makecpt -Cwysiwyg -T-44/48/1 > colors.cpt
ps=Geoid_TZ.ps
gmt grdimage geoid_TZ.grd -Cwysiwyg -R29/42/-13/0 -JM6.5i -P -Xc -I+a15+ne0.75 -K > $ps
gmt grdcontour geoid_TZ.grd -R -J -C0.25 -A1+f9p,25,black -Wthinner,dimgray -O -K >> $ps
gmt psbasemap -R -J -Bpxg4f1a2 -Bpyg2f1a2 -Bsxg2 -Bsyg1 \
   -B+t"Geoid gravitational model of Tanzania" -O -K >> $ps
gmt psscale -Dg27.5/-13.0+w16.5c/0.15i+v+o0.3/0i+ml+e -R -J -Ccolors.cpt \
   -Bg5f1a10+l"Color scale wysiwyg: 20 well-separated RGB colors [C=RGB, -T0/40/1]" \
   -I0.2 -By+lm -O -K >> $ps
gmt psbasemap -R -J \
   -Lx14.5c/-1.3c+c50+w200k+l"Mercator projection. Scale (km)"+f -UBL/-10p/-38p -O -K >> $ps
gmt pscoast -R -J -P -Ia/thinnest,blue -Na -N1/thickest,white -Wthinner -Df -O -K >> $ps
gmt pstext -R -J -N -O -K \
-F+f9p,13,black+jLB -Gwhite@50 >> $ps << EOF
39.5 -6.1 Zanzibar City EOF
gmt logo -Dx7.0/-2.0+o0.1i/0.1i+w2c -O -K >> $ps
gmt pstext -R0/10/0/15 -JX10/10 -X0.1c -Y11.3c -N -O -F+f10p,13,black+jLB >> $ps << EOF
3.0 9.0 World geoid image EGM2008 vertical datum 2.5 min resolution EOF
gmt psconvert Geoid_TZ.ps -A0.5c -E720 -Tj -Z
```

4. GMT script used for plotting Fig. 5: Free-air gravity anomaly of Tanzania.

```
gmt img2grd grav_27.1.img -R29/42/-13/0 -Ggrav.grd -T1 -I1 -E -S0.1 -V
gmt grdcut grav.grd -R29/42/-13/0 -Gtz_grav.nc
gdalinfo -stats tz_grav.nc
gmt makecpt -Chaxby -T-200/200/1 > colors.cpt
ps=Grav_TZ.ps
gmt grdimage tz_grav.nc -Ccolors.cpt -R29/42/-13/0 -JM6.5i -I+a15+ne0.75 -Xc -K > $ps
gmt psscale -Dg27.5/-13.0+w16.5c/0.15i+v+o0.3/0i+ml+e -R -J -Ccolors.cpt \
        -Bg25f5a50+l"Color scale 'jet' (Dark to light blue, white, yellow and red [C=RGB] -183/278/1)" -I0.2 -
By+lmGal -O -K >> $ps
```

```
gmt grdcontour tz_grav.nc -R -J -C25 -A50 -Wthinnest -O -K >> $ps
gmt pscoast -R -J -P -Ia/thinner,blue -Na -N1/thickest,red -W0.1p -Df -O -K >> $ps
gmt psbasemap -R -J -Bpxg1f0.5a1 -Bpyg1f0.5a1 -Bsxg2 -Bsyg1 -B+t”Free-air gravity anomaly for Tanzania” -O -K
>> $ps
gmt psbasemap -R -J \
        -Lx14.5c/-1.5c+c50+w200k+l”Mercator projection. Scale (km)”+f -UBL/0p/-40p -O -K >> $ps
gmt psbasemap -R -J -Tdx1.0c/0.4c+w0.3i+f2+l+o0.15i -O -K >> $ps
gmt pstext -R -J -N -O -K \
-F+f9p,13,black+jLB -Gwhite@50 >> $ps << EOF
39.5 -6.1 Zanzibar City
EOF
gmt pstext -R0/10/0/15 -JX10/10 -X0.1c -Y11.3c -N -O \
  -F+f10p,13,black+jLB >> $ps << EOF
3.0 9.3 Global satellite derived gravity grid (CryoSat-2 and Jason-1).
EOF
gmt psconvert Grav_TZ.ps -A0.5c -E720 -Tj -Z
```

5. GMT script used for plotting Figs 6–9: Geomorphometric mapping by R.

```
library(sp)
library(raster)
library(ncdf4)
library(RColorBrewer)
library(sf)
library(tmap)
alt = getData(“alt”, country = “Tanzania”, path = tempdir())
slope = terrain(alt, opt = “slope”)
plot(slope)
aspect = terrain(alt, opt = “aspect”)
plot(aspect)
hill = hillShade(slope, aspect, angle = 40, direction = 270)
plot(hill)
plot(alt)
tmap_mode(“plot”) # here example for the slope map.
map1 <-
  tmap_style(“gray”) +
  tm_shape(slope, name = “Slope”, title = “Slope”) +
  tm_raster(title = “Slope (0\u00B0-90\u00B0)”, palette=”plasma”, style=”quantile”, n = 6,
    breaks = c(5, 15, 30, 60, 75, 90),
    legend.show = T,legend.hist = T,legend.hist.z=0) +
  tm_scale_bar(width = 0.25,text.size = 0.8, text.color = “black”,
    color.dark = “black”, color.light = “white”,
    position=c(“left”, “bottom”), lwd = 1) +
  tm_compass(type = “radar”, position=c(“right”, “top”), size = 10.0) +
  tm_layout(scale = .8,
    main.title = “Slope terrain analysis based on DEM of Tanzania. Mapping: R”, main.title.position = “center”,
    main.title.color = “black”, main.title.size = 1.0,
    title = “Slope (0\u00B0-90\u00B0)”,
    title.color = “black”, title.size = 1.0,
    title.position = c(“left”, “top”), panel.labels=c(“R packages: tmap, raster, sp, sf”),
    panel.label.color = “darkslateblue”,
    panel.label.size = 1.0, legend.position = c(“left”,”bottom”),legend.bg.color = “grey90”,
    legend.bg.alpha = .2, legend.outside = FALSE, legend.width = .3, legend.height = .5,
    legend.hist.height = .2, legend.title.size = 0.9,
```

```
    legend.text.size = 0.8, inner.margins = 0) +
  tm_graticules(
    ticks=TRUE, lines=TRUE,labels.rot = c(15, 15), col="azure3", lwd=1,labels.size=1.0)
map1
tmap_save(map1, "Tanzania_Slope.jpg", dpi=300, height=10)
```

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Ruumiandmestiku visualiseerimine Tansaania kraatoni Serengeti tasandiku ja Ida-Aafrika riftioru näitel

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Planeedi keskkonnaprotsesside analüüsimisel on oluline roll ruumiandmetel ja nende visualiseerimisel. Erinevatest allikatest pärit andmete maht suureneb tänapäeval kiiresti ning koos sellega peavad arenema ka kartograafilised meetodid. Keerulise geoloogilise ehitusega piirkondade kaardistamine nõuab kompleksset käsitlust. Käesolevas töös on analüüsitud ja visualiseeritud Tansaania ruumiandmeid, kasutades vahendeid nagu Generic Mapping Tools (GMT), R ja QGIS. Viis loodud kaarti iseloomustavad looduslikke tingimusi (geoloogia, geofüüsika, topograafia) ning neli visualiseerivad geomorfomeetrilist analüüsi. Kahemõõtmelised kaardid ja kolmemõõtmeline pinnamudel loodi kasutades konventsionaalset GIS tarkvara koos skriptimisega. Geomorfomeetrilised kaardid (kõrgusmudel, nõlvad, varjutus) loodi statistikatarkvara R skriptide abil.