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# Seismicity in the Afar Depression and Great Rift Valley, Ethiopia

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Integrated mapping is essential in geological studies to assess risks of earthquake hazards. Cartographic techniques have become a commonplace approach to visualizing data in the continuous geologic and geophysical fields. However, traditional GIS mapping is a manual process with a time-consuming workflow that can lead to mistakes and misinterpretation of data. This study applied two mapping approaches to address this problem: Generic Mapping Tools (GMT) used for automated cartographic workflow employing scripts and QGIS used for traditional geologic mapping. The study area includes Ethiopia, notable for its complex geologic setting. The study aimed to analyse the relationships between the geophysical, geological, topographic and seismic setting of the country by presenting six new thematic maps:

1 topography based on the GEBCO/SRTM15+ high-resolution grid;
2 geological units with consistent lithology and age from the USGS database;
3 geological provinces with major Amhara Plateau and Somali Province using USGS data;
4 geoid based on the Earth Gravitational Model 2008 (EGM-2008) grid;
5 free-air gravity anomaly model using satellite-based remote sensing data;
6 seismicity showing earthquakes and volcanos from 05/03/1990 to 27/11/2020.

The comparison of the topography, seismicity, geophysics and surface geology of the Afar Depression and the Great Rift Valley was based partly on extant literature on the geologic setting of Ethiopia which primarily focuses upon discussing tectonic processes that took place in the East African Rift System in the past. The current study contributes to the previous research and increases cartographic data on the geology and geophysics of Ethiopia. The outcomes can be implemented in similar regional projects in Ethiopia for geophysical and geological monitoring.

**Keywords:** geology, earthquakes, seismicity, cartography, mapping, GMT, Ethiopia

## Introduction

Geological and geophysical processes affect regional seismicity and geomorphologic structure. However, the geodynamic behaviour of the Earth makes these processes more sophisticated. For instance, gravity couples to thermally induced density contrast in the mantle of the Earth which results in increased stress. In turn, imposed stress and consequent deformation of solid rock affect rock rheology. Visualizing complex geologic phenomena requires advanced methods of cartographic visualization, such as integrated mapping. Integrated mapping is crucial to geological mapping in the following aspects. First, it enables visualization of the multi-source datasets (geologic, geophysical, topographic and seismic data from different origins). Second, it allows processing data from various open repositories linking maps from a thematic series into a geographic entity across the study area. Data with various origin and resolution (GEBCO, EGM-2008, geological vector layers, geophysical raster layers) can be mapped using various cartographic techniques (Balestro & Piana, 2007; Lemenkova, 2020a, 2020b; Karam et al., 2011; Suetova et al., 2005; Schenke & Lemenkova, 2008; Gauger et al., 2007; Pulsifer et al., 2008; Lindh & Lemenkova, 2021).

For applications of the integrated mapping, each dataset (geophysical, topographic, geologic, tectonic) is generalized for use at a particular extent and spatial scales. For instance, clipping the area, set up of coordinate projection and resolution of the graphics (300 or 600 dpi in TIFF or other formats). The solution of complex data processing by a multi-tool cartographic approach combines various software and transfer data to different tools for an optimized workflow. Such a decision promises tighter integration of the geologic, geophysical and topographic data, better processed using a format-specific software where ArcGIS-native .shp files are processed by the QGIS, while .ngdc format of earthquakes tabular data is processed in a Generic Mapping Tool (GMT). Since each cartographic tool has a specific layout design, this necessarily requires its adjustment in a map series. It can be an identical coordinate extent or a projection defined for all the maps. Nevertheless, the integration of various tools for complex mapping presents a new cartographic functionality aimed to improve the existing GIS approaches through more flexible mapping techniques (Desalegn & Mulu, 2021; Bagyaraj et al., 2019; Klaučo et al., 2013a, 2013b; Ahmad et al., 2020).

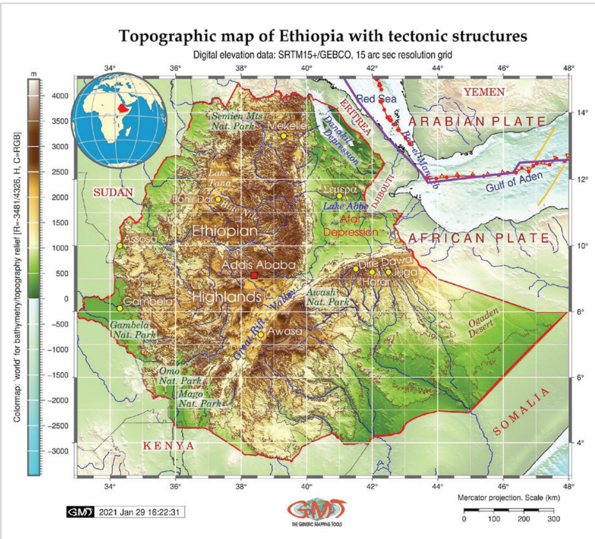
This study demonstrated the implementation of such an integrated mapping which applies both traditional GIS and scripting GMT techniques. Its advantage consists in flexibility of the workflow for geologic mapping of Ethiopia. This research aims to assess the variations in geophysical, seismic, and geologic parameters and analyses the correlation between these phenomena with the country's topography. It was achieved through the integrated cartographic approach which combined GMT scripting methods and QGIS for modeling and visualization of the high-resolution data. Using both methods, this paper provides examples of integrated data processing, visualization and mapping for two different modes: (1) GMT used to plot geophysical, seismic and topographic data; (2) QGIS used for assessment of geologic setting using USGS datasets, and descriptive geologic analysis from published literature. This resulted in a series of new maps of Ethiopia, which can help better understand this region's complex relationships of geologic, topographic, and geophysical settings. The advantage of the traditional GIS is that it is easy to use and does not require advanced programming knowledge necessary to write scripts. However, in contrast to the traditional GIS, GMT is a tool that saves time when plotting geospatial data, helping to ensure reproducibility of maps for cartographic analyses, while traditional mapping is a time-consuming routine that cannot be easily reproduced. By saving time of data analysis through automation, GMT provides a more systematic and fast mapping workflow, minimizing the risk of cartographic errors. Thus, it constitutes an advanced tool that can be incorporated into geologic studies with mapping needs.

## Materials and methods

### Study area

Ethiopia (33°E–48°E, 3°N–15°N) is known above all for its contrasting topography (*Fig. 1*) shaped by complex geologic processes and tectonic influence of active East African Rift continental rift zone. The geology of Ethiopia was outlined previously in studies on tectonics, petrology, geochemistry and volcanism (Gass, 1970; Hutchinson & Engels, 1970; George et al., 1998; Hagos et al., 2016; Hunt et al., 2020; Bosworth, 1992, 1994). The most prominent geologic objects of the country include the Ethiopian Highlands and the Afar Depression presenting a notable, morphologically contrasting part of its topography.

**Fig. 1.** *Topographic map of the study area. Mapping: GMT*




*Source: author*

The formation of the Afar Triple Junction dates back to the Early Miocene (23–25 M). At the same time, the individualization of spreading axes where new oceanic crust is generated is recent, i.e., less than 1.3 M. (Barberi & Varet, 1978). Major geologic forces of its formation include the complex tectonic-rift interactions. Specifically, it concerns the convergence between the Nubian, Somalian and Arabian Plates along the Zagros fold and thrust belt, and the uplift of the Afar Dome (Corti et al., 2015). The combination of these forces increased by rising mantle plume resulted in a break up of the Arabian–Nubian Shield (Beyene & Abdelsalam, 2005). As a result, the Afar Depression presents a junction area of the three large tectonic structures: the Red Sea, Gulf of Aden, and East African Rift System (Tazieff & Varet, 1971). The triple-spreading ridges of the Red Sea and the Gulf of Aden show up on land and connect with the East African Rift near Lake Abbe (*Fig. 1*).

The Afar Triangle is the only place on Earth where an oceanic rift develops within a continent. It presents an active tectonic area where the crust is slowly drifting apart, which results in a recurring sequence of repetitive earthquakes with long deep fissures in the terrain, and the valley floor sinking in the Afar Depression (Wright et al., 2006). The new igneous crust under Afar has been generated during the early development of the Red Sea basin at magmatic rift zones (Mohr, 1989). The evolution and nature of the faulting, analysis of the distribution and ages of volcanoes (Barberi et al., 1972), comparison of seismic and gravity data indicate that the eastern rift lies along a zone of the progressive crustal thinning with local crustal disruption (Baker et al., 1972). As a result, thinned continental crust is absent beneath the Afar Depression except for the Danakil Block.

As a result of unique tectonic processes, the Afar Depression is notable for active tectonic elements, such as spreading segments, volcanoes crossing regional faults with transverse structures, numerous NNW-oriented normal faults, and multiple geothermal sites (Varet & Gardo, 2020; Varet, 2020). Two essential active volcanic chains include Erta'Ale Range and Alayta Range (Barberi et al., 1970). Afar's dynamic seismic events were recorded in late 2005 when 15 earthquakes greater than M5 and a small volcanic explosive eruption occurred within the Afar Rift at the Dabbahu volcano and Erta Ale volcanoes (Ayele et al., 2007).

## Data and software

The study uses General Bathymetric Chart of the Oceans (GEBCO) data as a basis for topographic mapping (*Fig. 1*). GEBCO has been developed and maintained by the International Committee as an initiative for precise topographic mapping of the Earth with unprecedentedly high resolution (Schenke, 2016; GEBCO Compilation Group 2020). Complex aspects of bathymetric mapping by GEBCO are discussed regarding its quality, spatial resolution and precision compared with other topographic grids, e.g. ETOPO1 (Lemenkova, 2020c, 2020d, 2020e).

The geoid visualization (*Fig. 4*) is based on the Earth Gravitational Model 2008 (EGM2008) dataset (Pavlis et al., 2012). The geologic data (*Figs. 2* and *3*) are retrieved from the USGS (Pollastro et al., 1999). The marine free-air gravity grid was based on satellite remote sensing data (Sandwell & Smith, 1997; Sandwell et al., 2014). Two leading software tools have been used for cartographic visualization and data processing: 1) Generic Mapping Tools (GMT) scripting toolset version 6.1.1. (Wessel et al. 2019); and 2) QGIS version 3.16 (QGIS.org, 2021).

### Cartographic visualization

The GMT-based mapping (*Figs. 1, 4, 5*, and *6*) was performed using the scripting approach. The GMT-based maps were compiled using a combination of GMT modules used to plot every cartographic element by the lines of code. For example, the topographic mapping (*Fig. 1*) utilised 'grdimage' module in the following code: 'gmt grdimage et_relief.nc -Cpauline.cpt -R33/48/3/15 -JM6.5i -I+a15+ne0.75 -t60 -Xc -P -K > $ps'. The study area was then clipped using the 'psclip' GMT module in the following code: 'gmt psclip -R33/48/3/15 -JM6.5i Ethiopia.txt -O -K >> $ps'. The color palette was selected as 'world' and applied the following code with the '-T-3481/4326' showing actual elevation range: 'gmt makecpt -Cworld.cpt -V -T-3481/4326 > pauline.cpt'.

The visualization of the geoid (*Fig. 4*) was carried out using the two files in the original adf format, a raster data format that stores spatial data as a binary grid of rows and columns of cells that comprise together the total grid. These files were converted to the GMT format using the code 'gmt grdconvert n00e00/w001001.adf geoid_IQ.grd' and 'gmt grdconvert n00e45/w001001.adf geoid_IR.grd'. Afterwards, the images were inspected using gdal 'gdalinfo geoid_IR.grd -stats' to check the data range. The color palette was generated using the expression 'gmt makecpt -Chaxby -T-50/10/1 > colors.cpt'. The coloring was applied using the following scheme: 'gmt grdimage geoid_IR.grd -Ccolors.cpt -R33/48/3/15 -JM6.5i -P - Xc -K > $ps'.

Because the initial map has not supplied with contours and could therefore not be readily analyzed, plotting isolines for a better reading of values was performed using the code 'gmt grdcontour geoid_IR.grd -R -J -C1 -A1+f9p,25,black -Wthinner,dimgray -O -K >> $ps'. Adding cartographic legend was done by the code 'gmt psscale -Dg33.0/2+w16.0c/0.15i+h+o0.3/0i+ml -R -J -Ccolors.cpt -Bg5f1a10+l"Color scale: haxby for geoid and gravity [R=-107/23/1, C=RGB]" -I0.2 -By+lm -O -K >> $ps'. The initial file generated by GMT was in a PostScript format. Therefore, to put the file into a known acceptable format, it was converted using the code 'gmt psconvert Geoid_ET.ps -A0.5c -E720 -Tj -Z'.

Mapping gravity (*Fig. 5*) was performed using the code 'gmt grdimage et_grav.nc -Ccolors.cpt -R33/48/3/15 -JM6.5i -I+a15+ne0.75 -Xc -K > $ps'. The geological lines and points in the map of seismicity (Fig. 6) were added using the 'psxy' module: 'gmt psxy -R -J volcanoes.gmt -St0.4c -Gred -Wthinnest -O -K >> $ps'. The earthquakes were added using the code 'gmt psxy -R -J quakes_ET.ngdc -Wfaint -i4,3,6,6s0.1 -h3 -Scc -Csteps.cpt -O -K >> $ps', where the '-i4,3,6,6s0.1' flag generates the points of the earthquakes using the table values of earthquake magnitude, depth and coordinates.

Several variables related to the tectonic setting of Ethiopia were visualized by GMT, for instance, tectonic plates boundaries were added using the following code 'gmt psxy -R -J TP_Arabian.txt -L - Wthicker,purple -O -K >> $ps'. The ridges were added using the code: 'gmt psxy -R -J ridge.gmt -Sf0.5c/0.15c+l+t -W thin,red -Gyellow -O -K >> $ps'. The geologic mapping (*Figs. 2* and *3*) were performed using QGIS software. The geologic units (*Fig. 2*) and provinces (*Fig. 3*) were visualized using standard cartographic tools: Layer Managements and Layout Manager. The background map is presented by the OpenStreetMap layer connected via the Web/QuickMapServices plugin of QGIS.

## Results and discussion

### Topographic mapping

A complex and highly contrasting relief of Ethiopia formed due to the geologic evolution, and tectonic processes present the topographic heterogeneity. Thus, according to the GEBCO/SRTM15+ remote sensing data inspected by GDAL, the country's topography varies from –3.481 km (Gulf of Aden) to 4.326 km in the Ethiopian Highlands. The most critical factors that sculptured such a diverse modern topographic shape of Ethiopia include the formation of the East African Rift and the

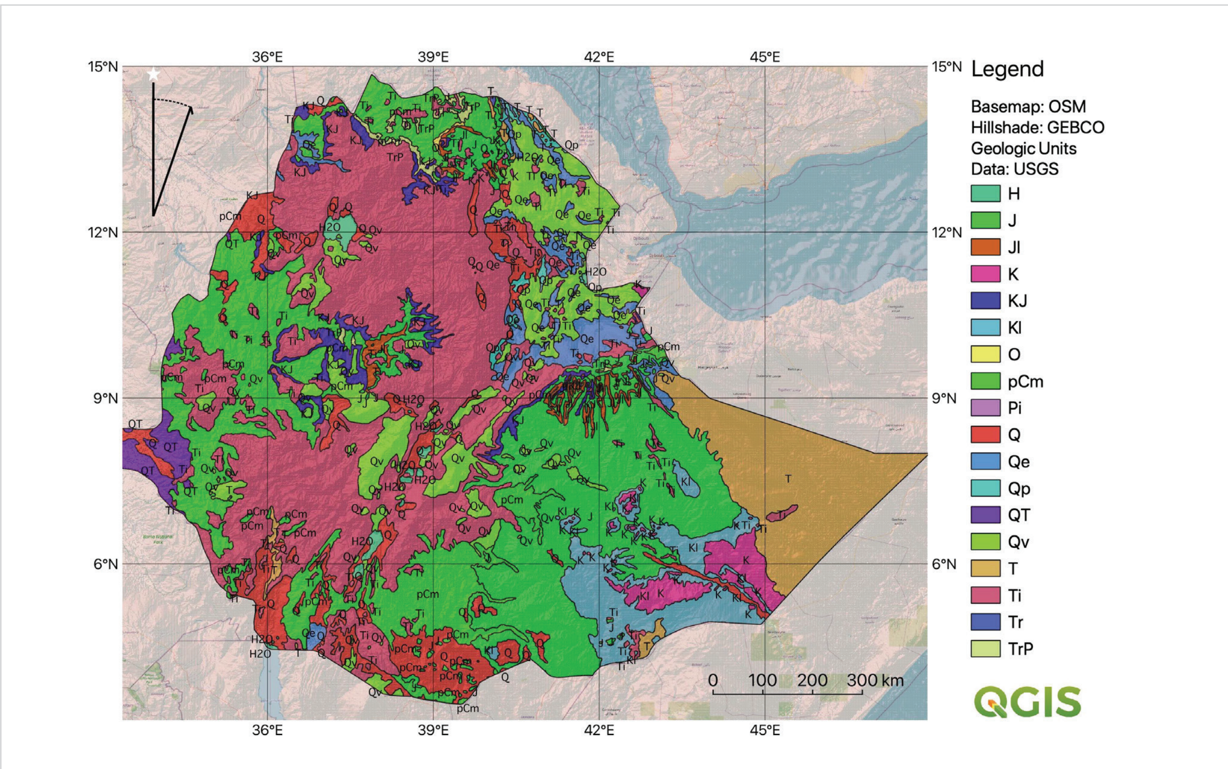
Afar Triple Junction, as well as the opening of the Red Sea as a result of the lithospheric plate movements, volcanic activity, and rifting (Bosworth, 2015; Chorowicz, 2005). Besides, tectonic and climate processes also largely control sedimentation patterns and surface geology, as discussed in previous papers (Cerling & Powers, 1977; Gohl et al., 2006a, 2006b; Ali Kassim et al., 2002). In turn, the topographic variability of the country creates excellent conditions for the formation of diverse local habitats providing environmental conditions for a variety of species during climate extremes. The topographic map of Ethiopia (*Fig. 1*) was visualized both for the geological comparison (*Figs. 2* and *3*) and for the interpretation of the geophysical setting (*Figs. 4, 5*, and *6*) based on its present geomorphological features.

## Geologic mapping

The geological structure of Ethiopia (*Fig. 2*) has been strongly affected by rifting and volcanic processes, as shown in *Fig. 6*, reflected in the geomorphological structure and topography of the country. The most prominent geologic units include the outcrops and facies of the Cretaceous Jurassic (KJ), Jurassic (J), and Cretaceous (K), among others. The Quaternary (Q), Quaternary eolian/aeolian (Qe), and Tertiary intrusives (Ti) environments are primarily found in the Afar (*Fig. 2*). Other significant outcrops include the basaltic rocks of early Tertiary (T), corresponding to the Somali Plateau and Ogaden Desert in NE Ethiopia.

The volcanic activity of the Quaternary age occurred in the eastern part of the country (*Fig. 2*), including

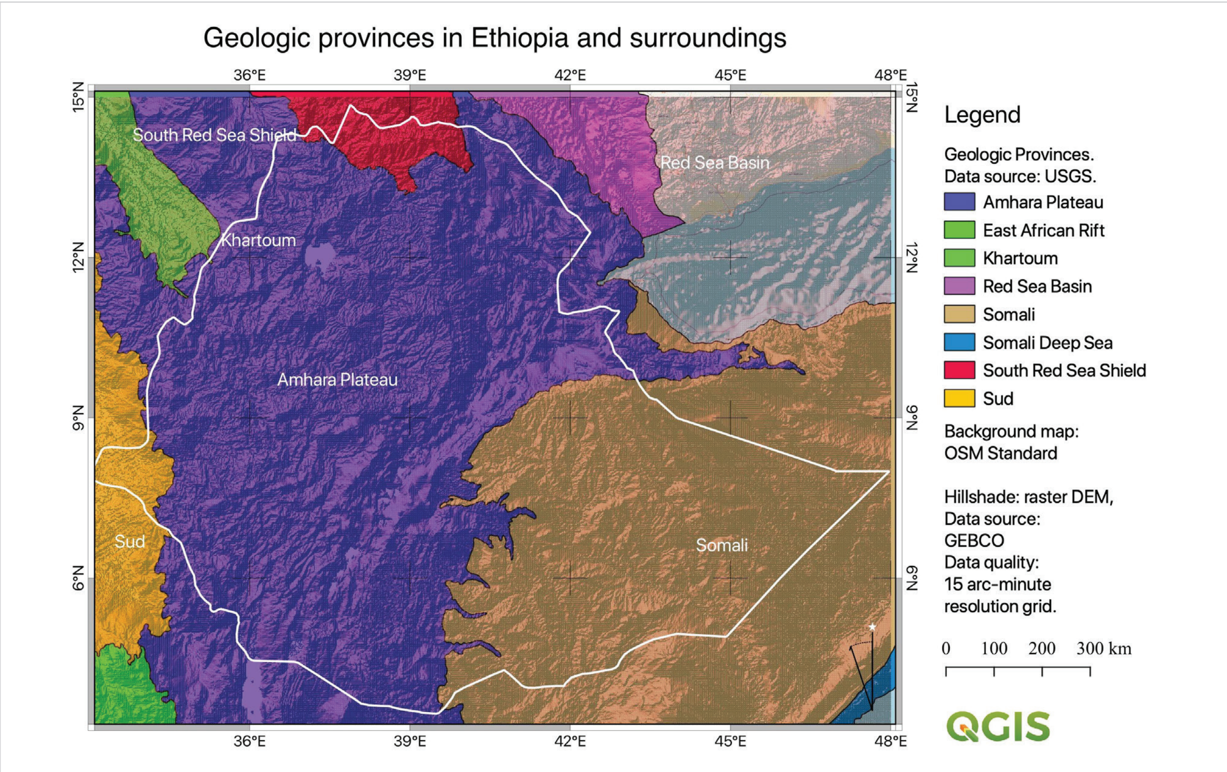
**Fig. 2.** *Geologic units in Ethiopia. Mapping: QGIS*




*Source: author*

the Afar Depression, which corresponds to the previous findings (Kalb, 1978) and shows remains of the volcanic features preserved on the Somali Plateau and the area east of the Great Rift Valley (compare *Figs. 1* and *2*). The tectonic evolution of the rift valley has about east-west direction, as also reported in previous studies (Le Pichon & Francheteau, 1978). The Tertiary intrusives (Ti) and flood basalts with basaltic and felsic volcanic rocks are the dominating geologic units in the country's west, covering a significant part of the Ethiopian Highlands (*Fig. 2*). The Precambrian and Cambrian undifferentiated units (pCm) are found in the southern regions of the country (*Fig. 2*). The geologic provinces (*Fig. 3*) show the general division of the country into two large units: the Amhara Plateau (slate blue colour) and the Somali Plateau (bisque colour). The latest one is a part of the Ethiopian Plateau, composed of the Simien Mountains National Park, Lake Tana with Blue Nile outflows, and Omo and Mago National Parks in the south of the country. The Gambela National Park is predominantly located in the Sud province. The small northern region includes the South Red Sea Shield province boarding the Danakil Depression.

**Fig. 3.** *Geologic provinces in Ethiopia. Mapping: QGIS*



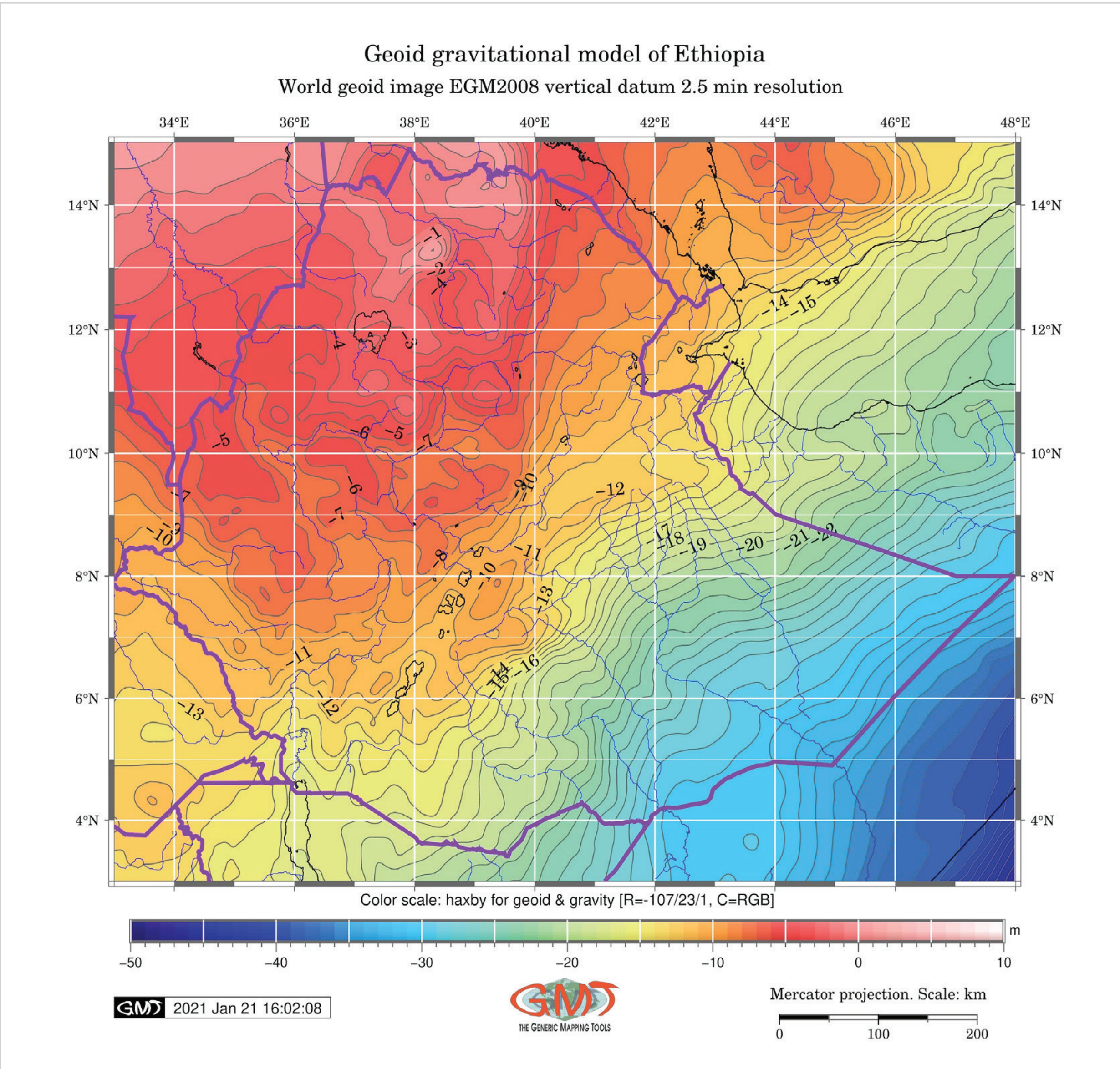

*Source: author*

Compared with the previous geologic maps of Ethiopia (Kazmin 1972, 1975; Kazmin & Berhe, 1981; WoldeGabriel et al., 1990; Yirgu et al., 2006; Salvini et al., 2012), this study presents the updated maps based on the detailed vector data received from the USGS using QGIS. The proposed geological maps visualized a sequence of unites (*Fig. 2*) and provinces *Fig. 3*), as well as volcanic activities and earthquakes using recent data from the IRIS dataset (*Fig. 6*). The undulations of the geoid (*Fig. 4*) and free-air gravity anomalies (*Fig. 5*) demonstrate intensive gravity variations. The comparison of these maps reveals that the geological and geophysical setting of the area, in general, follows the topography that reasonably represents the rift structural pattern, directed approximately North-East to South-West. Moreover, current maps well match the existing cartographic works in previous studies. However, this research provides more details on Ethiopia's geological and geophysical features due to the high-resolution data and advanced methods of mapping.

## Geophysical mapping

The geophysical fields are represented on the geoid (*Fig. 4*) and free-air gravity anomalies in Faye's reduction (*Fig. 5*). The analysis of variations in free-air gravity anomalies over Ethiopia (*Fig. 5*) shows that the character of uplift is similar to the topographic highs observed on the topographic map (*Fig. 1*). For instance, the isolines of Faye's gravity well correlate with the topographic contours (*Figs. 1* and *5*). Hence, the geophysical mapping (*Figs. 4* and *5*) presents the analysis of the correlation between the modeled geoid and free-air gravity anomaly fields, with geologic, topographic, and seismic data of Ethiopia and major geomorphological areas, such as the Afar Depression and Ethiopian Highlands.

**Fig. 4.** *Geoid gravitational model of Ethiopia. Mapping: GMT*



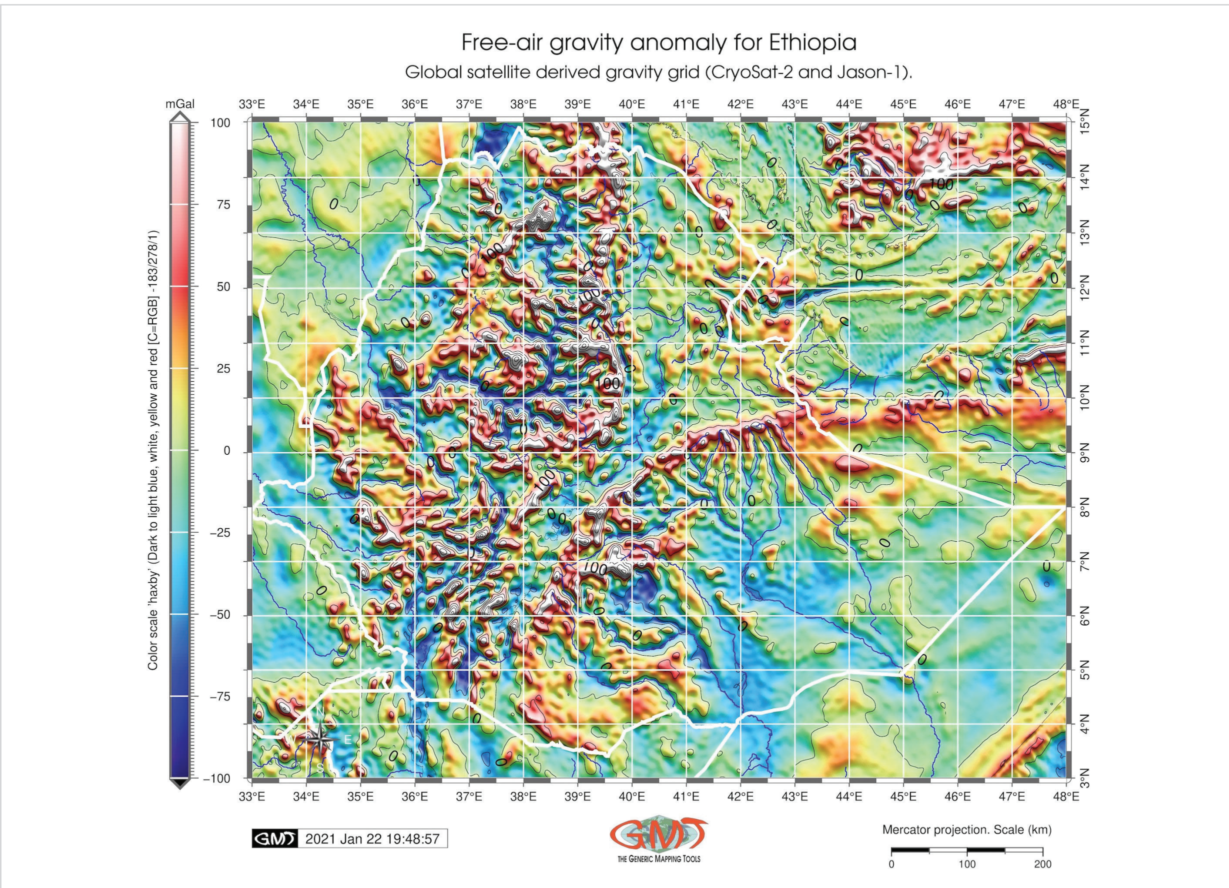

*Source: author*

The visualization of the free-air gravity anomalies in Faye's reduction revealed an increase in values above 50 mGal (*Fig. 5*), with a maximum of ca. 100 mGal in the highest peaks of the Ethiopian Highlands. This well corresponds to the topographic extent of the Ethiopian Highlands. On the contrary, the lowest values, that is, below –50 mGal, are typical for river valleys visible in the south and on the inter-mountainous valleys of the Ethiopian Highlands (compare *Fig. 1* with *Fig. 5*). The analysis of the free-air gravity anomalies suggests that the lithosphere beneath the Afar and Danakil depressions (which corresponds to the areas with 0 to –25 mGal) is reduced in density resulting in lower recorded values of gravity. These results support previously published reports on gravity fields in East Africa (Allan, 1970; Browne & Fairhead, 1983) and contribute through the updated mapping using modern tools and data.

The geoid visualized using EGM-2008 (*Fig. 4*) shows a distinct trend-oriented in NW-SE direction. This well corresponds to the general oblique orientation of the Great Rift Valley in Ethiopia (Mohr, 1962; Mohr & Gouin, 1976; Abebe et al., 2005; Corti, 2008). The values here generally decrease to the SE (–33 m) and reach the maximal NW (–1 m) in the Ethiopian Highlands. However, the general importance of geoid is negative, which might be, among others, the impact of the Indian geopotential height anomalies, which are the largest world's negative geoid values. In general, the geoid heights in Ethiopia tend to increase to the inner NW regions of the country and lower values in the SE and the Somali Plateau.

Gravity and seismic maps covering Ethiopia and surrounding water areas (the Red Sea and the Gulf of Aden) remain an essential issue in the context of geophysical

**Fig. 5.** *Free-air gravity anomalies over Ethiopia. Mapping: GMT*



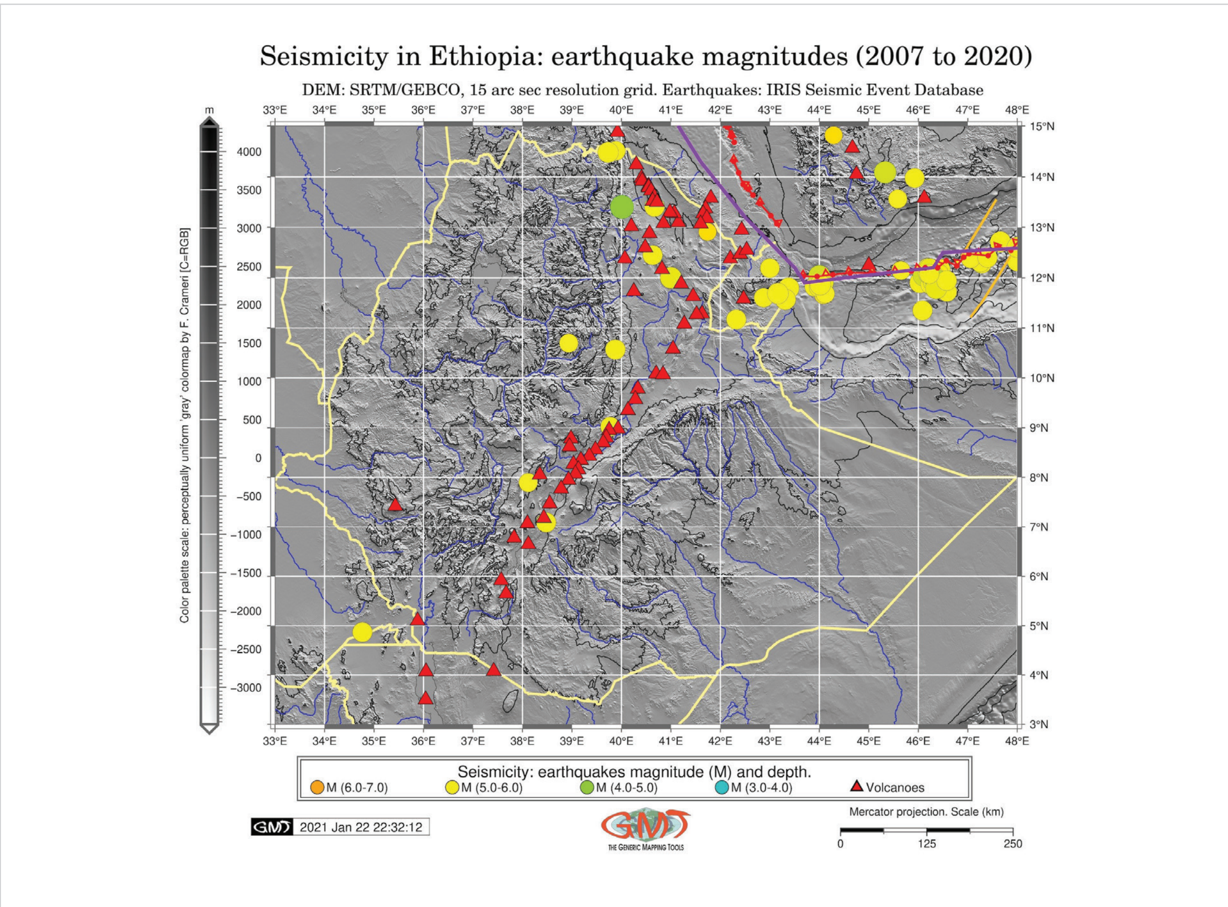

*Source: author*

research of Africa. The main mapping challenges associated with visualizing Ethiopia include detailed and automated mapping using high-resolution data and scripting techniques for a rapid workflow. New technologies of GMT used for plotting maps in *Figs. 1, 4, 5*, and 6 demonstrated effective solutions to finding new map styles and improving the topographic and geophysical content. The location of this region explains the need for detailed geophysical maps of Ethiopia in the tectonically active zone of the Great Rift Valley with recorded seismicity and volcanism.

## Mapping seismicity

Map of seismicity (*Fig. 6*) details the distribution of volcanoes and earthquakes over Ethiopia and their magnitude according to the IRIS (Incorporated Research Institutions for Seismology) dataset. The map analysis shows that volcanoes are mainly distributed along the Great Rift Valley. Besides, the seismicity is the highest in the Afar Triple Junction region, which continues to the east in the Gulf of Aden (*Fig. 6*). Comparing the distribution of earthquakes and volcanoes of Ethiopia (Fig. 6) to the topographic and geophysical maps (*Fig. 1* to *Fig. 5*) reveals correlations between the extent of the Great Rift Valley, the Afar Triangle, and the volcanoes located in this area. Besides, the distribution of the volcanism in the current map (*Fig. 6*) corresponds to the previous studies on the volcano-tectonic setting of Ethiopia and the Great Rift Valley (Civetta et al., 1975; Hart et al., 1989; Chernet et al., 1998; Hunt et al., 2020; Rouwet et al., 2021). The comparison of the distribution of earthquakes *(Fig. 6)* to the geoid model (*Fig. 4*) reveals that the Great Rift Valley, notable for the

**Fig. 6.** *Seismicity in Ethiopia: distribution of earthquakes and volcanoes. Mapping: GMT*




*Source: author*

volcanic activity (*Fig. 6*), clearly divides the two regions: the one with higher values of gravity (values over –10 m) and lower values (values below –10 m), respectively. The earthquakes are associated with continental rifting, particularly in seismically active regions like the Ethiopian Great Rift Valley. Therefore, mapping earthquakes and active volcanism contribute to assessing the risk of seismic hazards in Africa.

## Conclusions

Ethiopia is one of the most important geological regions of Africa. It has contrasting topography, extreme climate variability, and high seismicity, making it a geographically unique and distinct region. Besides, it is one of the most tectonically complex regions in the world due to the unique structure of the Afar Triple Junction and the Great Rift Valley. Several thematic geospatial datasets and two distinct cartographic approaches (GIS and GMT mapping) were linked to show the correlations between Ethiopia's topography, geophysical, seismic, and geologic settings to map such a complex region.

New topographic, geologic, geophysical, and seismic maps represent a helpful research tool for further geologic and geophysical investigation and comparative analysis concerning the topographic characteristics of Ethiopia. The presented maps were evaluated using comparative analysis to propose an investigation into the geographic setting of Ethiopia, based on the relationship between geology and the geophysical variables (e.g., geoid and gravity anomalies). Using these maps, this paper evaluated and visualized topographic, geoid, and gravity models to compare topography and seismicity. The location of volcanoes and earthquakes is associated with the Great Rift Valley and the Afar Depression, the most seismically active areas of the country. Accurate mapping enabled substantial correlations between these parameters in a series of thematic maps. The results demonstrated that the seismicity of the country is sensitive to the distribution of the rift zones and tectonic lineaments and corresponds well to the fault lines and topographic lowlands in the Afar Depression and the Great Rift Valley. The geoid undulations and free-air gravity anomaly patterns across the country were mapped, examined, and discussed for the associated geologic setting and topographic context of the relief in various parts of Ethiopia.

Despite widely used GIS in geosciences (Coltorti et al., 2009; Poppe et al., 2013; Klaučo et al., 2014; 2017; Lemenkova et al., 2012, Lemenkova, 2021; Sembroni et al., 2017), the application of GMT scripting in mapping continues to grow due to the advantages of the automatization in cartography achieved through coding (Gauger et al., 2007; Lemenkova, 2019a, 2019b, 2019c). The significant advantage of scripting consists in the increased precision, speed, and quality of data processing and visualization (Brus, 2019; Lemenkov & Lemenkova, 2021; Becker, 2005; Lemenkova, 2019d, 2020f; Pignalberi, 2021). This study presented the example of integrated mapping, a topic of increasing importance to geophysical studies and seismic hazard risk assessment in such geologically complex regions as Ethiopia. Using the presented maps, future studies could then focus on geomorphological mapping in such a way as to continue the thematic investigations of East Africa. The reported data can also be considered for use in other regions of Africa, which would bring benefits to geophysical and geologic explorations. The presented methods of GMT and QGIS can be repeated in similar studies that include cartographic visualization of geospatial datasets.

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