JOURNAL OF APPLIED ENGINEERING SCIENCES
ISSN: 2247-3769 / e-ISSN: 2284-7197

VOL. 12(25), ISSUE 2/2022
ART.NO. 346 pp. 191-202

SATELLITE ALTIMETRY AND GRAVIMETRY DATA FOR MAPPING MARINE GEODETIC AND GEOPHYSICAL SETTING OF THE SEYCHELLES AND THE SOMALI SEA, INDIAN OCEAN

Polina Lemenkova [a,*], O. Debeir [a]

[a] Université Libre de Bruxelles (ULB), École polytechnique de Bruxelles (Brussels Faculty of Engineering), Laboratory of Image Synthesis and Analysis (LISA), Bld. L, Campus de Solbosch, ULB – LISA CP165/57, Avenue Franklin D. Roosevelt 50, B-1050 Brussels, Belgium ORCID ID[*]: https://orcid.org/0000-0002-5759-1089, E-mails: *polina.lemenkova@ulb.be, olivier.debeir@ulb.be

Received: 06.03.2022 / Accepted: 10.04.2022 / Revised: 03.06.2022 / Available online: 15.12.2022

DOI: 10.2478/jaes-2022-0026

KEY WORDS: Somali Sea, Seychelles, Indian Ocean, Cartography, GMT, Geophysics.

ABSTRACT:

Evaluation of the representative cartographic techniques demonstrated that there are still considerable challenges facing the methods of marine geodetic, geophysical and bathymetric data visualisation. In an oceanic seafloor formation, the interaction between the geological structural elements and topographical relief can be analysed by advanced mapping. In present study, a correlation between geodesy, geophysics and topography has been examined including the following variables: geological structure, coastal topography and bathymetry, geophysical fields, free-air gravity anomalies and geoid undulation, sediment thickness, bathymetric patterns, and extension of the transform faults. The variables were visualised on the high-resolution raster grids using Generic Mapping Tools (GMT) scripting toolset. The study area is located in the Seychelles and the Somali Sea segment of the Indian Ocean. The data incorporates satellite-derived gravity grid, EGM-2008, geological structures, topography from GEBCO grid and GlobSed sediment thickness, processed by GMT scripts. The results demonstrated that western continental slope of Somalia is wide, gently declining to the seafloor at depths exceeding -5000 m. Kenya and Tanzania present a wide continental foot with depths ranging from -3500 to -5000 m. The Somali Sea basin shows low sedimentation lower than 500 m, while ridges and island chains have higher sediment influx (1,000-2,000 m). The Mozambique Channel has dominating values at 2,500-3,500 m. Higher values are noted near the Reunion and Mauritius islands until the Seychelles via the Mascarene Plateau (500 -1,000 m) against the <500 m in the areas of the Mid-Indian Ridge, Carlsberg Ridge and open water.

1. INTRODUCTION

1.1 Background

Recent advances in marine geodetic, bathymetric and geophysical surveying resulted in massive increase in volumes of data which requires processing these data collection for cartographic interpretation. Geophysical and topographic data visualisation by EGM-2008 and GEBCO datasets provide useful sources for the marine research in the West Indian Ocean region. Effective visualisation of such data by the advanced cartographic methods helps unveil hidden correlations between certain tectonic and geological phenomena. These might include, among others, faults and ridges, sediment thickness and bathymetric relief that can be well seen on the maps. Using high-resolution digital datasets is useful for studying remote locations and regions difficult to reach and study otherwise.

Besides, the in-situ oceanological investigations involve a difficult and costly process of organisation. For these reasons, many oceanographical and Earth studies use the advanced methods of mapping that resulted recent progress in geospatial data processing (Nonn et al. 2019; Trott et al. 2017; Lemenkova, 2020a, 2020b, 2022a; 2022b, 2022c). However, using traditional methods of GIS still remains a largely handmade and time-consuming process that raises a question of automation methods in cartographic workflow. Using scripting techniques enables more quick and precise data handling and plotting. A perfect example of scripting based cartographic toolset is presented by the Generic Mapping Tools (GMT) which consists of a wide variety of the specialised GMT modules used for plotting selected features on the maps.

* Corresponding author: Polina Lemenkova. Université Libre de Bruxelles (ULB), École polytechnique de Bruxelles, Laboratory of Image Synthesis and Analysis (LISA). E-mail: polina.lemenkova@ulb.be, Brussels, Brussels-Capital Region, Belgium.

Using scripts increase the accuracy, beauty and precision of maps which are valuable quality for various approaches in the geological and geophysical mapping.

In this paper, we handle all these cartographic challenged by applying GMT for effective visualisation of the topographic and geophysical raster grids in the study area of western Indian Ocean. For instance, different visualisation techniques of GMT modules are provided by such modules as 'pscontour' (for visualization of the isolines), 'makecpt' (for applying the color palette of the map), 'img2grd' (for data conversion), 'grdimage' (for raster visualization), etc. The cartographic projections can be selected based on the geographic location of the study area and applied by the 'psbasemap' module (Lemenkova 2022d). The created geophysical maps can be used consequently also by geologists in various research projects. Using topographic GEBCO DEM and geophysical datasets can successfully be accomplished by GMT scripting toolset, as demonstrated below in relevant sections.

1.2 Research Objectives

Mapping was carried out using GMT on the basis of the geologic, geophysical and bathymetric datasets. The hypotheses of this research are summarised in the following statements:

- Seafloor structure and geomorphic types can be detected using automatically techniques of GMT and high-resolution datasets to visualise topographic setting of the region affected by geological history and tectonic development of the West Indian Ocean in the past.
- Patterns of the geophysical data are detectable using semi-automated mapping using EGM-2008 data which can be achieved using GMT scripting methods.
- Hierarchical multi-source datasets (topography, geophysics, and geology) are valuable information sources for precise mapping of the seafloor.
- The topographic responses to the geophysical, geologic and environmental conditions of the seafloor formation in the past differ regionally in the Somali Sea segment of the West Indian Ocean.
- Scripting approaches of GMT can be used for automatic processing of geospatial data with aim at supportive precise geoinformation systems and geophysical monitoring and topographic data visualisation.

The paper also aims to investigate the driving geomorphological forces affecting submarine structure and bathymetry of the Seychelles by visualising a series of the thematic maps: topography, geophysical anomalies, geoid, and sediment thickness in the region. Overlaid with high-resolution topographic model based on the GEBCO/SRTM can be further used for analyses of DEM derivatives (such as submarine slopes, their aspects and ruggedness of the seafloor terrain). The presented maps can be applied and interpreted in geological and geophysical research domains with focus on Indian Ocean. Future application of the present study and maps can include integration of the cartographic illustrations with geophysical modelling, which can create a digital basis for target marine geophysical investigations. For example, overlay of the topographic maps (GEBCO) with geophysical data (EGM-based gravity grids) can support generating and expanding a database aimed to give additional data for geological prospecting and prognosis, as well as studying seafloor structure and estimate favourable locations for mineral resources exploration in the coastal regions of the East Africa.

1.3 Regional Setting

At first, some details will be introduced regarding the regional settings of the presented study area, which is located on the Somali Sea basin and the Seychelles, NW part of the Indian Ocean (Figure 1).

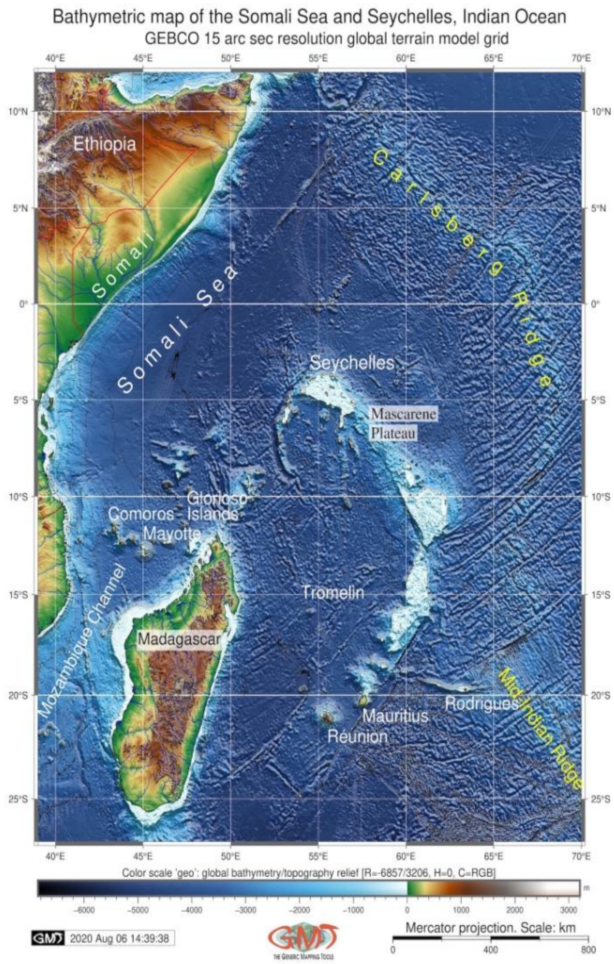

Figure 1. Topographic map of the Somali Sea basin and the Seychelles Bank and topography of the Madagascar and East African coasts, West Indian Ocean: The depths reach up to -6850 m, while maximal heights do not exceed 3200 m. Mapping: GMT. Map source: authors

The geographic location of this region can be brief characterised as follows. Its western part is presented by the Somali coasts which are known to be the longest national coastline (3025 km) in Africa with an estimated shelf area (up to -200 m) of 32500 km^2 (Carbone and Accordi, 2000). The southern border is naturally formed by the group of the northern end of Madagascar, the Amiranta ridge and the northern part of the Mascarene ridge, the Comoro Islands, Mayotte and the Glorioso Islands, Figure 1. Distinct geomorphological features presented by the Horn of Africa (Cashion et al. 2018) in the NW part of the Somali Sea. It stretches along the southern side of the Red Sea continuing its complex structure (Davies and Tramontini,

1970) where the system of faults controlled the trends of rifting. Further it extends into the Gulf of Aden, Somali Sea and a Guardafui Channel between the Socotra and the continent, the area generally known for fisheries (Sumaila and Bawumia, 2014). The Seychelles Islands are situated midway between the coast of Africa and the Carlsberg Ridge (Figure 1) with an almost flat top of the bank (Matthews and Davies, 1966).

The geology of the region is notable for complex setting, as reflected in previous studies on the geology of the Seychelles and the Somali Sea basin providing more detailes on this specific part of the West Indian Ocean (Berhe, 1986; Kröner and Sassi, 1996; Fantozzi and Ali Kassim, 2002; Koning et al., 1997; Leroux et al., 2020). The oldest portions of the Indian Ocean, which includes the study area of the Somali Sea and the Seychelles, were formed through the breakup of Gondwana and subsequent fragmentation of the East Gondwana (Davis et al., 2016).

The northern part of the Somali Sea is bordered by a continental slope of the Horn of Africa forming a sharp ledge with the Socotra Island (Böhnecke, 1935). Morphologically, the Socotra Island presents a fragment of the continental massif. Structurally, it forms a large uplifted structure in a continental platform being a part of the SE wing of the Arabian-Somali anteclise. It separated from the continental platform only in the Miocene. Former connections between the Socotra and the African continent are also proved by the presence of wadi on the island which present dry ephemeral riverbed valleys continuing the geomorphology from the Arabian Peninsula.

The geomorphology of the northern part of the Somali Sea was formed as a result of the collapse in the Gulf of Aden graben with a moderate spreading in the Aden-Sheba Ridge. The Somali margin is a magma-poor Iberian-type structure comprising a stretched proximal domain that passes seaward where the lower crust is completely thinned (Mortimer et al 2020). The slope overhang off the coast of Tanzania is associated with the horst uplifts of the sedimentary massifs of the Pemba, Zanzibar and Mafia islands (Lemenkova, 2022e). Minor troughs and grabens of the shelf and submarine margin of the continent (Figure 2) are filled with sediments from Triassic to Jurassic (McKenzie and Sclater, 1973).

Upper layered suite becomes thinner when moving towards the centre of the Somali Sea basin. It also sharply reduced in thickness behind the sedimentary barriers of the blocky basement ridges oriented approximately parallel to the strike of the continental slope. This also points at the impacts of the geomorphic and geologic settings. The ca. 300 km long seamount chain in the Eastern Somali Basin stretching NE-SW, seen in a quadrant between 50°-55°E and 3°-7°N (Figure 1).

The seamounts have probably originated due to melting and upwelling of upper mantle heterogeneities in advance of migrating of paleo Carlsberg Ridge as a result of the geochemical and tectonic evolution of the Indian Ocean mantle (Murton and Rona, 2015; Saha et al. 2020). The main tectonic events throughout the SW Somali Sea include the strike-slip movements along vertical faults. The deformation is localised within a narrow belt that extends for more than a 100 km in a NE–SW direction. The near parallelism between the fold axes and fault orientation indicates a right-lateral movements.

The geology of the Seychelles (Figure 2), with the largest Islands of the Mahé and Praslin, is dominated by the granitoid rocks and, to a lesser extent, by the basaltic dykes (Matthews et al. 1965).

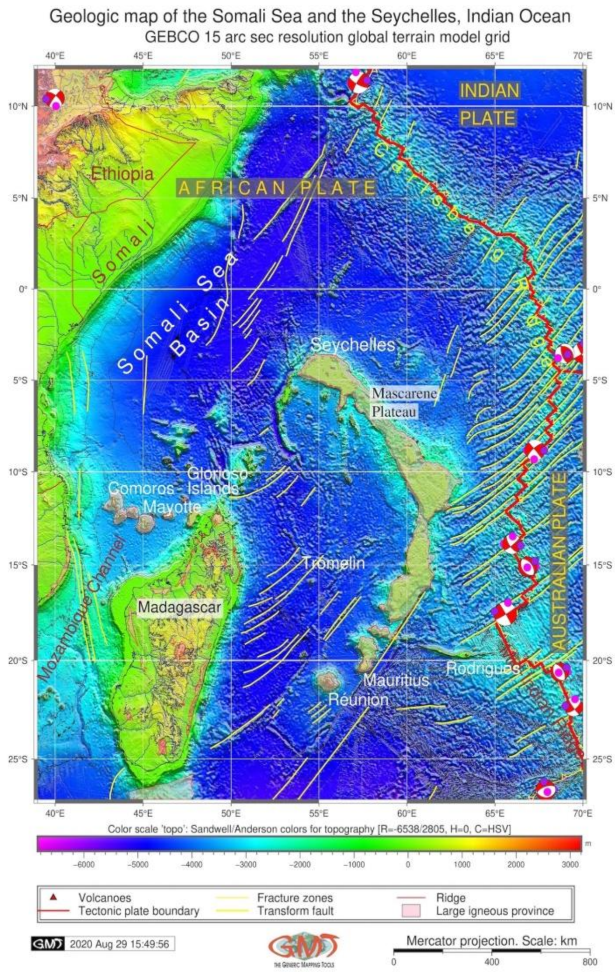

Figure 2. Geologic map of the Somali Sea basin the Seychelles Bank, Madagascar and the East African coasts, West Indian Ocean. It shows the location of ridges, large igneous provinces, lineaments (transform faults and fracture zones) and the extent of the tectonic plate boundaries. The faults are mostly oriented in SW-NE direction. Mapping: GMT. Map source: authors

The geomorphology of the Seychelles plateau presents a form of an arcuate wide, shallow bank of small islands (Figure 2). Specifically, it is being exposed as a series of granitic islands characterised as ferroan, metaluminous to peraluminous, alkali-calcic to calc-alkalic (Baker and Miller, 1963). The islands on the Amirante Bank are coral atolls and sand cays (Loncarevic, 1963) with the presence of basalts at a depth of less than 1 km beneath the atolls. Another presence of alkali olivine basalt shield volcanoes is distributed across the northern entrance of the Mozambique Channel, formed by the Comores Islands and a Tertiary volcanic province of northern Madagascar (Emerick and Duncan, 1982).

The Silhouette and North Islands in the Seychelles represent an alkaline plutonic–volcanic complex, dated at 63 to 63.5 Ma which might point at the link between the Seychelles magmatism. It was initiated by the peripheral activity of the mantle plume on the Réunion Island with the final stages of the cataclysmic Deccan Traps continental flood volcanism (67 to 63

Ma) that took place in India (Torsvik et al 2001). The severing of the Seychelles occurred by a SE ridge extension by the ca. 62 Ma (Collier et al. 2008). There are common traits in geologic history and magmatism of the Seychelles and southern India that are reflected in the geoid geopotential model (Figure 3).

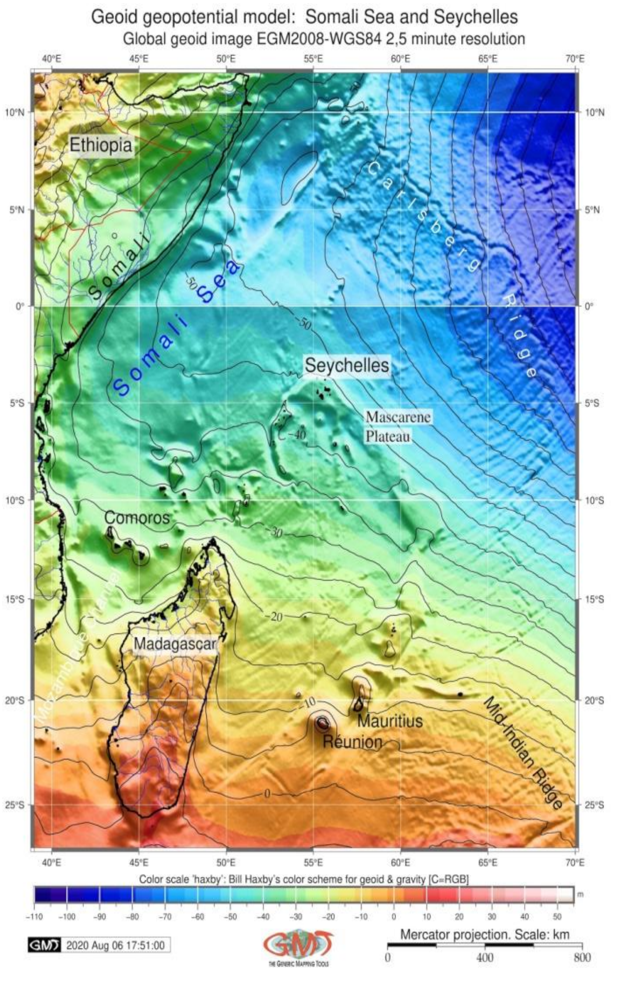

Figure 3. Geoid model of the Somali Sea basin, the Seychelles Bank, the Madagascar and East Africa. Mapping: GMT. Map source: authors

This corresponds to the similarity in trace element composition between the Seychelles suite and the Deccan alkaline felsic, granite and ultramafic rocks (Engel and Fisher, 1975). The spectrum of the rock types found on the Seychelles varies from gabbro, through syenite, to granite including olivine, plagioclase, ilmenite, clinopyroxene, alkali feldspar and apatite (Owen-Smith et al. 2013). Previous studies (Mart, 1988) pointed at the difference between the geological structure and origin of the Seychelles and Mascarene Plateau despite their geographical closeness and geomorphological similarity. Thus, the Seychelles are founded on the Precambrian granites while the Mascarene Plateau, from Saya de Malha Bank to Mauritius Island, is founded on Paleocene basalts (Roonwal, 1986).

The specifics of the deep circulation in the Somali Sea basin is presented by the inflow of bottom water into the Somali Basin through the Amirante Passage causing a thermohaline circulation, modulated by the monsoon wind forcing. Another notable feature consists in the deep western boundary current below at the base of the continental slope south of Socotra Island, which forms as part of a cyclonic bottom circulation (Dengler et al 2002).

Such specific oceanological setting creates favourable conditions for fishing due to the upwelling waters region in the Somali Sea resulting in the production of the macrofauna biomass of small organisms (Fieux and Swallow, 1988, Duineveld et al., 1997; Johnson et al., 1991). Some studies shown the dependance of the fluxes distribution of the sediment traps of the Somali Basin and the Monsoon upwelling presented examples of the aragonite pteropods (Klöcker et al., 2006; Singh and Conan, 2008) and the organic burial of cysts (Zonneveld and Brummer, 2000). Besides, the distribution of the mangroves forests, well developed in the Seychelles, especially on its largest island Mahé, creates conditions for additional sediment deposits and accumulation (Woodroffe et al., 2015).

2. MATERIALS AND METHODS

All presented maps have been prepared employing the Generic Mapping Tools (GMT) (Wessel and Smith, 1991), on open source cartographic scripting software toolset originally developed in 1987 by Paul Wessel and Walter H. F. Smith, U.S.A. and being constantly updated thereafter by the developers team (https://www.generic-mapping-tools.org/) (Wessel et al. 2013, 2019). The GMT was created in UNIX OS but the maps were plotted using the Mac OS (MacBook Air, Mac OS Monterey, Apple M1 chip 8-core CPU, 2020). The cartographic design of final maps, including general layout, projections, appearance of cartographic elements and colour palettes, was applied using technical options from the GMT.

The topographic map (Figure 1) shows characteristics of the bathymetry in the Somali Sea basin including local submarine features and geomorphology. The map (Figure 1) has been plotted based on the GEBCO grid (GEBCO Compilation Group, 2020) and the grids were processed by GDAL library (GDAL/OGR contributors, 2020, 2020) for data inspection.

Mapping geophysical properties of the seafloor (Figure 4) included the geoid Earth Gravitational Model (EGM-2008) at 2,5 arc-min resolution grid (Pavlis et al. 2012), which is in turn based on the updated and improved EGM96 dataset (Lemoine et al 1998). The marine free-air gravity anomalies represent the satellite-derived gravity grid (Sandwell et al. 2014). The contours of the continents and oceans were plotted using available vector based data of GMT (Wessel and Smith, 1996).

A series of the thematic maps covering study area of the Somali Sea and the Seychelles were made using the GMT scripting toolset. By combining the GMT syntax and its technical approach for mapping with quality raster data, the study area of the Somali Sea and the Seychelles was visualized aimed at the analysis of the geophysical and topographic setting. The codes and writing of GMT scripts was done using existing approaches and descriptions (Lemenkova, 2020c, 2021b, 2021c).

In a cartographic simulation, visualisation of the raster grids was approximated by the 'grdimage' module, e.g. for the gravity map (Figure 3), with the following example of the code: 'gmt grdimage ss_grav.nc -Ccolors.cpt -R270/-65/340/-45r -JA318/-57/5.5i -P -I+a15+ne0.75 -Xc -K > $ps'. The data conversion has been done by 'img2grd' module: 'img2grd grav_27.1.img -R270/371/-72/-44 -Ggrav.grd -T1 -I1 -E -S0.1 -V'.

A thorough compilation of the Somali Sea geoid data from 4 grids (Figure 4) allows interpreting the geoid undulations through about the basin. The compilation has been performed using several steps in a cartographic workflow:

- Conversion of binary-format grid into the file via the GMT 'grdconvert' module with a GRD extension by the following code: grdconvert n00e45/EGM2008som1.grd. The same procedure was repeated for the surrounding grids (quadrants with the coordinates: n00e00, s45e45, s45e00).
- The data extent was checked for each grid using GDAL utility by the code gdalinfo EGM2008som1.grd -stats.
- The colour palette was defined using the GMT 'makecpt' module using the data from the preliminary step (extent): gmt makecpt -Chaxby.cpt -V -T-110/55/1 > colors.cpt.
- The PostScript file was initiated by the line ps=Geoid_Som.ps, following by the image visualization: 'gmt grdimage EGM2008som1.grd -Ccolors.cpt -R39/70/-27/12 -JM6i -P -I+a15+ne0.75 -Xc -K > $ps' The same procedure has been repeated for each of the four grids.
- The isolines were plotted using 'grdcontour': gmt grdcontour EGM2008som1.grd -R -J -C5 -A10 -Wthinner -O -K >> $ps as in similar studies (Lemenkova, 2019b).
- The annotations and texts were plotted using a 'pstext' module, e.g.: gmt pstext -R -J -N -O -K -F+jTL+f13p,Helvetica,black+jLB+a-53 >> $ps << EOF 64.7 -20.1 Mid-Indian Ridge EOF, as explained in previous studies in more details (Lemenkova, 2019c)
- Additional cartographic elements (scale, grid ticks, title, legend, color palette) were plotted using a set of modules 'psbasemap', 'psscale', 'pscoast'. The final file was converted to an image by a 'psconvert' GMT module.

The geoid undulations are shown in Figure 3 showing the western segment of the West Indian Ocean. Significantly higher values of geoid occur in the SW region, southward off Madagascar and the Reunion Island, while the lowest values are notable in the NE off the Carlsberg Ridge. Gravity data (Figure 4) have been used to examine the seafloor and terrestrial morphology over the study area in a quadrant 39°E/70°E/27°S/12°N in Somalia defined by the CryoSat-2 and Jason-1 altimeters (Sandwell et al. 2014). Map shows variations in the free-air gravity anomalies in the segment of the West Indian Ocean: the Somali Sea, the Seychelles Bank and neighbouring areas of the Madagascar and the East African coasts. Values range from -100 to 100 mGal (Figure 4). The sedimentary layer (Figure 5) was plotted using the GlobSed (Straume et al. 2019), both of which are used due to their high-quality and precision as the homogeneous and high-resolution materials. The maps were plotted using GMT developed by P. Wessel and W. H. F. Smith in 1991 and continuously updated thereafter (Wessel and Smith, 1991, Wessel et al., 2013).

3. RESULTS

The submarine features of the bathymetry in the Somali Sea segment of the Indian Ocean and the Seychelles bank area is visualised on the topographic map (Figure 1). The shelf zone extending along the coasts of Somalia, Kenya and Tanzania, on the eastern border of the African continent, presents a very narrow strip of land. However, the continental slope is rather wide, with slopes gently declining to the seafloor bottom generally lying at depths exceeding -5000 m. Such specific geomorphological pattern can be seen on the isolines of the western sector of the sea (Figure 1). In the southern part of the region, the continental slopes of Kenya and Tanzania gradually transform to a very wide continental foot with dominating depths from -3500 up to approximately -5000 m, according to the GEBCO grid inspected by GDAL (dark blue in Figure 1).

Refined geoid gravitational model based on the image EGM-2008 with unprecedentedly high-resolution covering the Somali Sea and the Seychelles was not reported earlier in this spatial extent, projection and spatial resolution. It revealed a general trend oriented in SW-NE direction in the geoid heights (Figure 1). It shows values >5 m and higher characteristic for the Madagascar Island.

The Mozambique Channel shows general decrease in values in the NE direction which has slightly negative values at -30 m (light green to aquamarine colours, Figure 4) starting from the Comoros Islands. Such specific pattern points at impact from the local tectonic setting, including the extent of the active fault system in the oceanic lithosphere of the Mozambique Channel (Deville et al. 2018). As for the most basin of the Somali Sea, it demonstrates a general distribution of values from -30 to -50 m (aquamarine colours in Figure 4).

The satellite-derived marine free-air gravity anomalies (Figure 3) are mapped using satellite-based data. Such high-resolution raster grids enable to detect various tectonic features of the seafloor ocean and contribute to a better understanding of regional geological setting and features: faults, fracture zones, mid-ocean ridges, rises, trenches, seamounts. This is especially true for the areas of basins covered by the thick layer sediments. Comparing Figure 3 with Figure 1 enables to detect such lines and specific topographic and geomorphological structures that mirror the tectonic lines in the region (Bird, 2003).

It furthermore points at the continental type of the crust under the flat-topped Seychelles Bank. Correlation between the marine free-air gravity and the topography is supported by previous studies that investigated and compared the tectonic and geomorphological setting of the West Indian Ocean with gravity data. They reported that transferred crustal block bounded by inner pseudofault and failed spreading ridge is characterised by a gravity low, rugged basement and the crustal structure of the Seychelles (Davies and Francis, 1964; Sreejith et al. 2016).

The satellite-derived free-air gravity data (Figure 3) shows traces of an EW-trending extinct spreading ridge (3°-4°S, 47,0°E-49,5°E), as well as a NS-oriented fracture zones (4°-9°N, 51,0°E-53,5°E) both located within the basin of the Somali Sea segment of the Indian Ocean.

In such a way, this map added new information to the previous studied. Based on the 1:1 000 000 Gravity Anomaly Map of Somalia for 2.5D gravity modelling earlier study (Rapolla et al., 1995) reported that crystalline basement in the southern Somali Sea is transformed to a denser material and is of oceanic nature.

The sediment thickness (Figure 5) over the Somali Sea has a clearly asymmetric type of distribution with a dominating orientation NE-SW. Map is showing the variations in sediment thickness in the seafloor in selected segment of the West Indian Ocean: the Somali Sea and the Seychelles Bank. The values range from 0 in the open water areas of the Indian Ocean

(Carlsberg Ridge) up to 5550 m in the coastal area of the Somali Sea A greater thickness is observed along the coasts of Tanzania (up to 5,250 m), while central basin has lower values <1,000m.

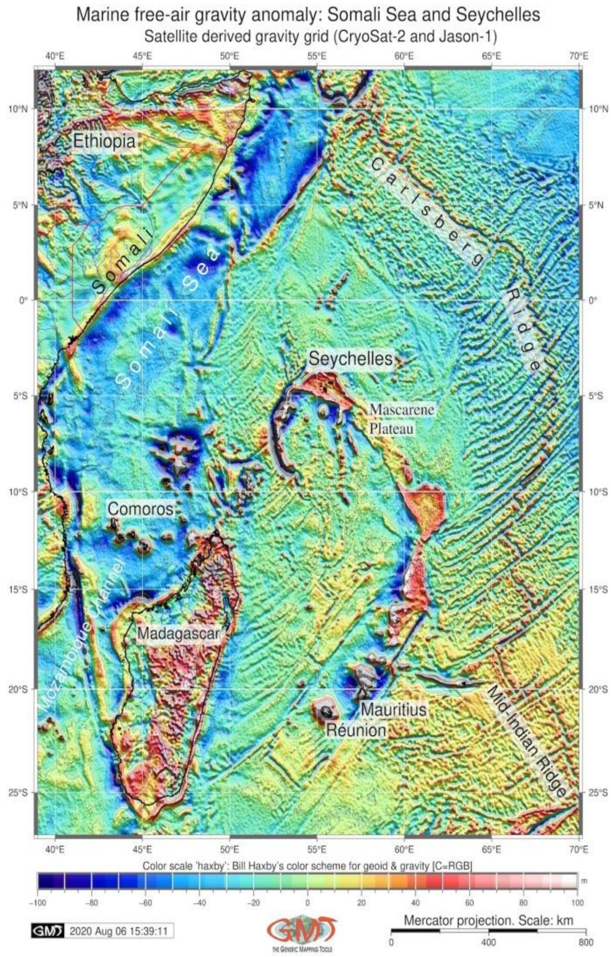

Figure 4. Marine free-air gravity anomaly of the Somali Sea basin and the Seychelles. Mapping: GMT. Map source: authors

The sediment thickness over the Somali Sea has an asymmetric type of distribution oriented in NE–SW. The highest values of the sediments along the coasts of Tanzania reach up to 5,250 m while the central basin have generally low dominating values <1,000m (dark blue colours in Figure 5).

Such a pattern in sediment coverage is also supported by previous studies (Ali Kassim et al. 2002) where two main earlier sedimentary basins were defined in the southern Somalia, trending in NE–SW direction: the Mesozoic-Tertiary Somali coastal basin and the Mesozoic Luuq-Mandera basin.

Spatial variations are noted as the extreme thickness of the Triassic sediments in the axial part of the Somali basin, and the thinner and younger succession on both sides of the basin.

Comparing to the very low sedimentation in the open Somali Sea areas with values below 500 m (Figure 5), the ridges and island chains have higher sediment influx with values between 1,000 to 2,000 m.

The Mozambique Channel has dominating values at a range of 2,500 to 3,500 m, the region NW off the Madagascar coasts has a dominating range at 2,500 to 3,000 m of the sediment layer (Figure 5). A striking correlation between the sediment thickness and the topography can be seen along the arc of the Seychelles in Figure 1 and Figure 4:

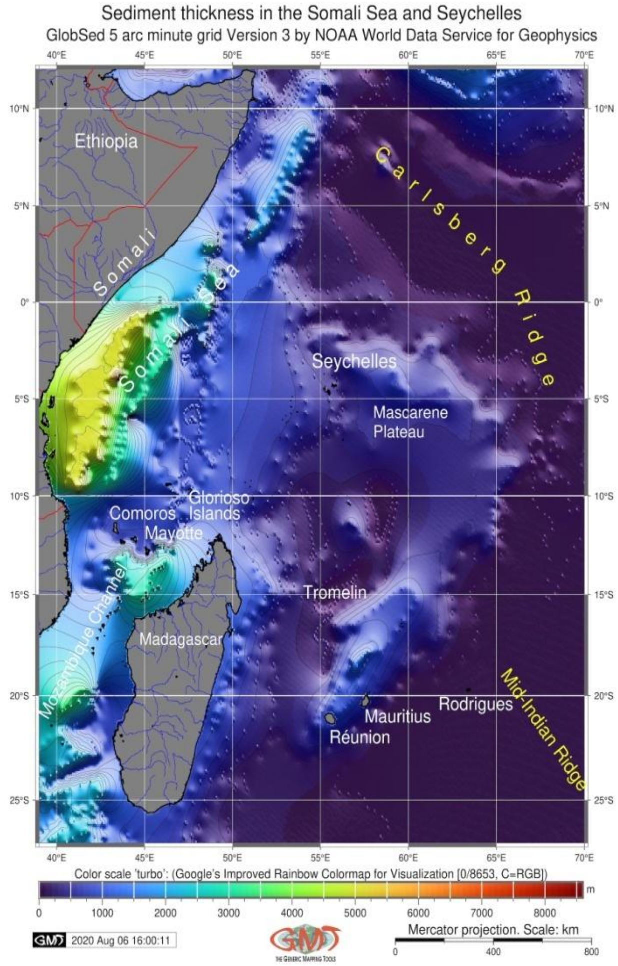

Figure 5. Sediment thickness in the Somali Sea seafloor and the Seychelles. Mapping: GMT. Map source: authors

The region starting from the Reunion and Mauritius islands on the south and continuing in an arcuate form until the Seychelles via the Mascarene Plateau has clearly higher values comparing to the surrounding open ocean areas, a 500 to 1,000 m for the Seychelles against the values below 500 m in the Mid-Indian Ridge, Carlsberg Ridge and open water areas, which prove previous studies (Ewing and Ewing, 1967; Ewing et al. 1969; Kolla and Kidd, 1982).

Comparing to the earlier works (Schott et al. 1975; Bunce and Molnar, 1977; Singh et al., 1999), the thickness of sedimentary layer along the coasts of Somalia in western Somali Sea exceeds 2000 m reaching its maximum (up to 10,000 m) along the coasts of Kenya and up to 6,000-9,000 m on the shores of Tanzania (Bunce et al., 967).

Thus, this study shows a more detailed visualisation of the sedimentation pattern in the region with more refined and actual results achieved due to the GMT plotting. We detected 4,750 to 5,250 m of sediment strata as maximal values near the Tanzania coasts (Figure 5, mustard-coloured elongated areas).

The sediment thickness along the continental slope is very high and in its lower part exceeds 6000 m.

The unconsolidated sediments consist of two formations:

1) the upper one is layered, largely composed of turbidites;
2) the lower one is acoustically transparent.

The lower suite has seismic wave velocities of 2.2 km/s, followed by a layer with velocities of 3.5-5.3 km/s, which diapirs force into brittle overlying rocks at the lower suite.

About a half or a third of these strata are terrestrial deposits e.g. the Karoo Formation (Catuneanu et al., 2005), the most widespread stratigraphic unit in Africa south of the Kalahari Desert (Bordy and Catuneanu, 2001).

The accumulation of these formations in the south, in Mozambique and Madagascar, resulted in the formation of basalt covers. In turn, the basaltic covers were replaced by the accumulation of marine, but mainly shallow-water sediments, which began in the Middle Jurassic and Early Cretaceous.

This is a good indication of the large-scale and intense subsidence of the continental margins in the western part of the Indian Ocean. It was at this time that the main features of the morphology of the continental margin of the Somali Basin were formed.

A remarkable feature of the Somali Sea basin consists in the appearance of the granite and basalt layers in the deepest part of the Somali Sea Basin which well correlates with depths of 5000–5340 m. Quite unexpectedly, the appearance of the granite layer is under the Seychelles, that is, along with oceanward direction from the mainland.

Such geological structure of the Earth's crust in this area undoubtedly indicates at an existing extensive block (i.e. a microcontinent), which submerged since the Jurassic. In particular, it is proved by the presence of continental rocks of the Karoo Series beneath the sea water level.

In the Seychelles, the crustal section has a typically continental structure and continues for ca. 250 km to the SE to the Saia de Malia bank (Matthews and Davies, 1960).

Besides a series of the geological and geophysical maps and relevant literature analysed and discussed in this paper. Technical details of the GMT-based data visualisation by scripting workflow were presented and demonstrated to be effective approach of mapping that enables automation of data handling and refine aesthetic visualisation of geospatial data.

Practical use of open source datasets on geophysical and topographic phenomena (GEBCO, GlobSed and EGM-2008, CryoSat-2 and Jason-1 gravity grids) covering the Somali Sea and the Seychelles was introduced as well, which can be used as a reference for similar studies as a reference.

4. DISCUSSION

The study has provided cartographic visualisation of the western segment of the Indian Ocean, the Somali Sea and the Seychelles, showing the complexity of the marine geophysical and topographic setting in this region. The refinements in correlation between the topographic and geophysical data are based on mapping the unprecedentedly high-resolution raster grids: GEBCO, EGM-2008, satellite-derived gravity anomalies from the CryoSat-2 and Jason-1.

This enabled to depict geomorphological and tectonic structure of the seafloor in a detailed view including selected features: faults, ridges, graben, horst and their spatial extensions in the Somali Sea basin.

Available geophysical and topographic raster data and geological information were used as a background and a basis for the performed analysis of the study region.

The relief of the oceanic seafloor results from the effects of previous geologic development and tectonic formation in the earlier history of the Earth.

The bathymetry of the Indian Ocean in general and its western segment in particular is being ultimately shaped by the concurrent and diverse driving forces of geological and tectonic character. Other controlling factors include paleogeographic evolution, climate change fluctuation that affected sedimentation through iceberg melt in Antarctic and debris flow in the coastal areas of the East Africa. Finally, oceanological processes largely intervene in the circulation of the deep waters that significantly contributes to the basin sedimentation.

5. CONCLUSION

The use of GMT, demonstrated in this paper, proposes smart solutions to geophysical mapping through automated methods of scripting, as a replacement of laborious manual workflow of traditional GIS.

The advanced methods of GMT were applied to accurate and aesthetic mapping of the western segment of the Indian Ocean wit ha special focus on geological and geophysical investigation of the Somali Sea and the Seychelles. In such a way, this paper contributed to the geological studies of the Somali Sea and the Seychelles using advanced mapping.

The advancements in modern cartography largely depend on the use of the cutting edge technologies, such as scripting and machine learning.

Geospatial data analysis supported by advanced scripting techniques can ensure smart geophysical mapping and precise data visualisation for a better and more in-depth analysis of the complex submarine regions such as western Indian Ocean. The present paper demonstrated the application of the developed advanced methods of mapping by GMT scripting approach for systematic operative monitoring of marine geophysical phenomena and distribution of major submarine geomorphological landforms in the Seychelles bank using high-resolution spatial data.

With this aim, the applied scripting approach and choice of GMT methodology are largely explained by the effectiveness of the machine learning and scripting techniques for automation of mapping workflow using high-resolution data, as a perspective mapping method in marine geophysical studies. The needs of machine learning application consist of high speed and accuracy of data handling for geophysical and geological data analysis and effective visualisation.

The increasing amount of regular bathymetric survey using updated technical tools resulted in increasing volume of high-quality bathymetric and geophysical data. These data require fast, accurate and automatic processing. The GMT-based data processing has a high potential for such tasks, supportive geophysical modelling, geological forecasting and prognosis and decision making in oceanological monitoring.

This triggers challenges of the effective use of GMT while handling marine geophysical and oceanological data can be summarised in the following key points:

- converting raw geophysical and bathymetric data to meaningful information (submarine seafloor patterns and geomorphic landform types);
- transferring information to knowledge (interpreting geophysical anomalies and associated geological structures present in this particular region);
- applying knowledge in decision making and smart solutions for marine geological and oceanological investigations in the remotely located regions;

The long-term perspectives and benefits of using GMT for cartography consist in more effective, automated, rapid, and accurate mapping process which results in print-quality aesthetic maps for geological, bathymetric and geophysical monitoring.

The GMT approach in its syntax and principle of data processing is closely related to the programming often used in geosciences, e.g. Python, R or scripting languages (Lemenkova, 2019a; Dobesova and Dobes, 2012; Lemenkov and Lemenkova, 2021). The GMT structures and interrelates both vector and raster types of geodata treating them as complex informational layers through a module-based “overlay” where it stills resembles of GIS (Mathew and Nethaji Mariappan, 2014; Klaučo et al., 2013, 2017; DeVasto et al., 2020; Lemenkova, 2021d; Greenfield and Lawson, 2020). However, GMT completely lacks the traditional GUI. Such a scripting approaches increases speed and precision of mapping process enabling to focus on the understanding and analysis of the complexity of geological phenomena by their correlation.

The structure of the GMT script recalls a framework of machine learning and geospatial data processing, especially in terms of multi-source use of information in various formats that can be converted both using the 'psconvert' module and by the integration of GDAL. While each module contributes to the final map by overlay of the additional elements on a map, the resulting figure presents a multi-layered image received from such an iterative process of GMT coding. These are briefly the main advantages of the GMT that were considered when selecting the main instrument of research.

Based on the existing experience (Lemenkova, 2020d, 2021a), the GMT scripting toolset has proven to be an excellent methodological cartographic framework that makes it possible to visualise and analyse complex geological and geophysical data. Another advantage of the GMT consists in its flexibility of data reading in a variety of acceptable formats (NetCDF, GRD, GMT native, C-binary format, ESRI Arc/Info ASCII, GEODAS grid, Golden Software Surfer, AGC, GDAL) which enables to process and present printing-quality maps.

Data Availability Statement

The GMT codes are available on the GitHub: https://github.com/paulinelemenkova/Mapping-Somali-Sea-and-the-Seychelles.

6. ACKNOWLEDGEMENTS

This project was supported by The Federal Public Planning Service Science Policy or Belgian Science Policy Office, Federal Science Policy – BELSPO (B2/202/P2/SEISMOSTORM).

We thank the two anonymous reviewers for their useful comments and critical suggestions on the initial version of the text which improved the manuscript.

References

Ali Kassim, M., Carmignani, L., Conti, P., Fantozzi, P.L., 2002. Geology of the Mesozoic-Tertiary sedimentary basins in southwestern Somalia. *J. African Earth Sci.*, 34(1–2), 3-20. https://doi.org/10.1016/S0899-5362(01)00102-6.

Baker, B.H., Miller, J.A., 1963. Geology and geochronology of the Seychelles Islands and the structure of the floor of the Arabian Sea. *Nature*, 199(4891), 346-348.

Berhe, S.M., 1986. Geologic and geochronologic constraints on the evolution of the Red Sea-Gulf of Aden and Afar depression. *J. African Earth Sci.*, 5(2), 101-117. https://doi.org/10.1016/0899-5362(86)90001-1.

Bird, P., 2003. An updated digital model of plate boundaries. *Geochemistry, Geophysics, Geosystems,* 4(3), 1027. https://doi.org/10.1029/2001GC000252.

Böhnecke, G., 1935. Geographie des Indischen und Stillen Ozeans. *Naturwissenschaften,* 23, 830–832. https://doi.org/10.1007/BF01491916.

Bordy, E.M., Catuneanu, O., 2001. Sedimentology of the upper Karoo fluvial strata in the Tuli Basin, South Africa. *J. African Earth Sci.*, 3(3–4), 605-629. https://doi.org/10.1016/S0899-5362(01)00090-2.

Bunce, E., Langseth, N. G., Chase, R.L., Ewing, M., 1967. Structure of the western Somali basin. *J. Geophys. Res.*, 72(10), 2547-2555. https://doi.org/10.1575/1912/6138.

Bunce, E.T., Molnar, G. 1977. Seismic reflection profiling and basement topography in the Somali basin: Possible zones between Madagascar and Africa. *Ibid*, 82(33), 5305-5311. https://doi.org/10.1029/JB082i033p05305.

Catuneanu, O., Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H., Hancox, P.J., 2005. The Karoo basins of south-central Africa. *J. African Earth Sci.,* 43, 211–253. https://doi.org/10.1016/j.jafrearsci.2005.07.007.

Carbone, F., Accordi, G., 2000. The Indian Ocean Coast of Somalia. *Marine Pollution Bulletin,* 41(1–6), 141-159. https://doi.org/10.1016/S0025-326X(00)00107-7.

Cashion, T., Glaser, S.M., Persson, L., Roberts, P.M., Zeller, D., 2018. Fisheries in Somali waters: Reconstruction of domestic and foreign catches for 1950–2015. *Marine Policy*, 87, 275-283. https://doi.org/10.1016/j.marpol.2017.10.025.

Collier, J.S., Sansom, V., Ishizuka, O., Taylor, R.N., Minshull, T.A., Whitmarsh, R.B., 2008. Age of Seychelles–India break-up. *Earth Planet. Sci. Lett.*, 272(1–2), 264-277. https://doi.org/10.1016/j.epsl.2008.04.045.

Davies, D., Tramontini, C., 1970. The Deep Structure of the Red Sea. *Philos. Trans. Royal Soc. A*, 267(1181), 181-189. https://doi.org/10.1098/rsta.1970.0031.

Davis, J.K., Lawver, L.A., Norton, I.O., Gahagan, L.M., 2016. New Somali Basin magnetic anomalies and a plate model for the early Indian Ocean. *Gondwana Res.,* 34, 16-28. https://doi.org/10.1016/j.gr.2016.02.010.

Davies, D. & Francis, T.J.G., 1964. The crustal structure of the Seychelles Bank. *Deep Sea Res. Part I Oceanogr. Res. Pap.,* 11, 921–927. https://doi.org/10.1016/0011-7471(64)90342-0.

Dengler, M., Quadfasel, D., Schott, F., Fischer, J., 2002. Abyssal circulation in the Somali Basin. *Deep-Sea Res. II: Top. Stud. Oceanogr..,* 49(7–8), 1297–1322. https://doi.org/10.1016/S0967-0645(01)00167-9.

DeVasto, M.A., Czeck, D.M., Bhattacharyya, P., 2012. Using image analysis and ArcGIS® to improve automatic grain boundary detection and quantify geological images. *Computers & Geosciences,* 49, 38-45. https://doi.org/10.1016/j.cageo.2012.06.005.

Deville, E., Marsset, T., Courgeon, S., Jatiault, R., Ponte, J.-P., Thereau, E., Jouet, G., Jorry, S.J., Droz, L. 2018. Active fault system across the oceanic lithosphere of the Mozambique Channel: Implications for the Nubia–Somalia southern plate boundary. *Earth Planet. Sci. Lett.*, 502, 210-220. https://doi.org/10.1016/j.epsl.2018.08.052.

Dobesova, Z. and Dobes, P., 2012. Comparison of visual languages in Geographic Information Systems. In: *2012 IEEE Symposium on Visual Languages and Human-Centric Computing (VL/HCC)*, 245-246. https://doi.org/10.1109/VLHCC.2012.6344536.

Duineveld, G.C.A., De Wilde, P.A.W.J., Berghuis, E.M., Kok, A., Tahey, T., Kromkamp, J., 1997. Benthic respiration and standing stock on two contrasting continental margins in the western Indian Ocean: the Yemen-Somali upwelling region and the margin off Kenya. *Deep-Sea Res. II: Top. Stud. Oceanogr.*, 44(6–7), 1293-1317. https://doi.org/10.1016/S0967-0645(97)00006-4.

Emerick, C.M. Duncan, R.A., 1982. Age progressive volcanism in the Comores Archipelago, Western Indian Ocean and implication for Somali plate tectonics. *Earth Planet. Sci. Lett.*, 30(3), 415-428. https://doi.org/10.1016/0012-821X(82)90077-2.

Engel, C.G., Fisher, R.L., 1975. Granite to ultramafic rock complexes of the Indian Ocean ridge system, Western Indian Ocean. *Geological Society of America Bulletin,* 86, 1553-1578. https://doi.org/10.1130/0016-7606(1975)86<1553:GTURCO>2.0.CO;2.

Ewing, J., Ewing, M., 1967. Sediment distribution on the mid-ocean ridges with respect to spreading of the sea floor. *Science*, 156, 1590-1592. https://doi.org/10.1126/science.156.3782.1590.

Ewing, M., Eittreim, S., Truchan, M., Ewing, J.E., 1969. Sediment distribution in the Indian Ocean. *Deep-Sea Res. Oceanogr. Abstr.*, 16(3), 231-232. https://doi.org/10.1016/0011-7471(69)90016-3.

Fantozzi, P.L., Ali Kassim, M., 2002. Geological mapping in northeastern Somalia (Midjiurtinia region): Field evidence of the structural and paleogeographic evolution of the northern margin of the Somalian plate. *J. African Earth Sci.,* 34(1–2), 21-55. https://doi.org/10.1016/S0899-5362(01)00100-2.

Fieux, M., Swallow, J.C., 1988. Flow of deep water into the Somali Basin. *Deep Sea Res. Part I Oceanogr. Res. Pap.,* 35(2), 303-309. https://doi.org/10.1016/0198-0149(88)90041-6.

GEBCO Compilation Group, 2020, GEBCO 2020 Grid. https://doi.org/10.5285/a29c5465-b138-234d-e053-6c86abc040b9.

GDAL/OGR contributors, 2020, GDAL/OGR Geospatial Data Abstraction software Library. Open Source Geospatial Foundation. https://gdal.org.

Greenfield, H.J., Lawson, K.S. 2020. Defining activity areas in the Early Neolithic (Starčevo-Criş) of southeastern Europe: A spatial analytic approach with ArcGIS at Foeni-Salaș (southwest Romania). *Quaternary International*, 539(20), 4-28. https://doi.org/10.1016/j.quaint.2018.09.042

Johnson, G.C., Warren, B.A., Olson, D.B., 1991, Flow of bottom water in the Somali Basin. *Deep-Sea Res.,* 38(6), 637-652. https://doi.org/10.1016/0198-0149(91)90003-X.

Klaučo, M., Gregorová, B., Stankov, U., Marković, V., Lemenkova, P., 2013. Determination of ecological significance based on geostatistical assessment: a case study from the Slovak Natura 2000 protected area. *Open Geosciences,* 5(1), 28–42. https://doi.org/10.2478/s13533-012-0120-0.

Klaučo, M., Gregorová, B., Stankov, U., Marković, V., Lemenkova, P., 2017. Land planning as a support for sustainable development based on tourism: A case study of Slovak Rural Region. *Environ. Eng. Manag. J.,* 2(16), 449-458. https://doi.org/10.30638/eemj.2017.045.

Klöcker, R., Ganssen, G., Jung, S.J.A., Kroon, D., Henrich, R., 2006. Late Quaternary millennial-scale variability in pelagic aragonite preservation off Somalia. *Mar. Micropaleontol,* 59(3–4), 171-183. https://doi.org/10.1016/j.marmicro.2006.02.004.

Kolla, V., Kidd, R.B., 1982. *Sedimentation and sedimentary processes in the Indian Ocean*. In: Narin A.E.M., Stehli F.G. (eds) The Ocean Basins and Margins, 6. The Indian Ocean. Plenum, New York, 1–50. https://doi.org/10.1007/978-1-4615-8038-6_1.

Koning, E., Brummer, G.-J., Raaphorst, W.V., Bennekom, J.V., Helder, W., Iperen, J.V., 1997. Settling, dissolution and burial of biogenic silica in the sediments off Somalia (northwestern Indian Ocean). *Deep-Sea Res. II: Top. Stud. Oceanogr.*, 44(6–7), 1341-1360. https://doi.org/10.1016/S0967-0645(97)00018-0.

Kröner, A., Sassi, F.P., 1996. Evolution of the northern Somali basement: new constraints from zircon ages. *J. African Earth Sci.*, 22(1), 1-15.

Lemenkov, V. and Lemenkova, P., 2021. Using TeX Markup Language for 3D and 2D Geological Plotting. *Foundations of Computing and Decision Sciences,* 46(3), 43–69. https://doi.org/10.2478/fcds-2021-0004.

Lemenkova, P., 2019a. Statistical Analysis of the Mariana Trench Geomorphology Using R Programming Language. *Geod. Cartogr.*, 45(2), 57–84. https://doi.org/10.3846/gac.2019.3785.

Lemenkova, P., 2019b. Topographic surface modelling using raster grid datasets by GMT: example of the Kuril-Kamchatka Trench, Pacific Ocean. *Reports on Geodesy and Geoinformatics*, 108, 9–22. https://doi.org/10.2478/rgg-2019-0008.

Lemenkova, P., 2019c. GMT Based Comparative Analysis and Geomorphological Mapping of the Kermadec and Tonga Trenches, Southwest Pacific Ocean. *Geogr. Tech*, 14(2), 39-48. https://doi.org/10.21163/GT_2019.142.04.

Lemenkova, P., 2020a. GRASS GIS for topographic and geophysical mapping of the Peru-Chile Trench. *Forum Geogr.*, 19(2), 143-157. https://doi.org/10.5775/fg.2020.009.d.

Lemenkova, P., 2020b. The geomorphology of the Makran Trench in the context of the geological and geophysical settings of the Arabian Sea. *Geology, Geophysics and Environment,* 46(3), 205-222. https://doi.org/10.7494/geol.2020.46.3.205.

Lemenkova, P., 2020c. Variations in the bathymetry and bottom morphology of the Izu-Bonin Trench modelled by GMT. *Bull. Geogr. Phys. Geogr. Ser.*, 18(1), 41–60. https://doi.org/10.2478/bgeo-2020-0004.

Lemenkova, P., 2020d. Using GMT for 2D and 3D Modeling of the Ryukyu Trench Topography, Pacific Ocean. *Misc. Geogr.*, 25(3), 1–13. https://doi.org/10.2478/mgrsd-2020-0038.

Lemenkova, P., 2021a. The visualization of geophysical and geomorphologic data from the area of Weddell Sea by the Generic Mapping Tools. *Studia Quaternaria*, 38(1), 19–32. https://doi.org/10.24425/sq.2020.133759.

Lemenkova, P., 2021b. Geodynamic setting of Scotia Sea and its effects on geomorphology of South Sandwich Trench, Southern Ocean. *Pol. Polar Res.*, 42(1), 1–23. https://doi.org/10.24425/ppr.2021.136510.

Lemenkova, P., 2021c. Submarine tectonic geomorphology of the Pliny and Hellenic Trenches reflecting geologic evolution of the southern Greece. *Rud. Geolosko Naft. Zb.*, 36, 4, 33–48. https://doi.org/10.17794/rgn.2021.4.4.

Lemenkova, P., 2021d. Dataset compilation by GRASS GIS for thematic mapping of Antarctica: Topographic surface, ice thickness, subglacial bed elevation and sediment thickness. *Czech Polar Rep.*, 11(1), 67–85. https://doi.org/10.5817/CPR2021-1-6.

Lemenkova, P., 2022a. Console-Based Mapping of Mongolia Using GMT Cartographic Scripting Toolset for Processing TerraClimate Data. *Geosciences*, 12(3), 140. https://doi.org/10.3390/geosciences12030140

Lemenkova, P., 2022b. Handling Dataset with Geophysical and Geological Variables on the Bolivian Andes by the GMT Scripts. *Data*, 2022; 7(6), 74. https://doi.org/10.3390/data7060074

Lemenkova, P., 2022c. Mapping Climate Parameters over the Territory of Botswana Using GMT and Gridded Surface Data from TerraClimate. *ISPRS International Journal of Geo-Information*, 11(9), 473. https://doi.org/10.3390/ijgi11090473

Lemenkova, P., 2022d. Cartographic scripts for seismic and geophysical mapping of Ecuador. *Geografie*, 127, 195–218. https://doi.org/10.37040/geografie.2022.006

Lemenkova, P., 2022e. Tanzania Craton, Serengeti Plain and Eastern Rift Valley: mapping of geospatial data by scripting techniques. *Estonian Journal of Earth Sciences*, 71(2), 61–79. https://doi.org/10.3176/earth.2022.05

Lemoine, F.G., Kenyon, S.C., Factor, J.K., Trimmer, R.G., Pavlis, N.K., Chinn, D.S., Cox, C.M., Klosko, S.M., Luthcke, S.B., Torrence, M.H., Wang, Y.M., Williamson, R.G., Pavlis, E.C., Rapp R.H., Olson, T.R., 1998. The Development of the Joint NASA GSFC and the National Imagery and Mapping Agency (NIMA) Geopotential Model EGM96. NASA/TP-1998-206861, July 1998.

Leroux, E., Counts, J.W., Jorry, S.J., Jouet, G., Révillon, S., BouDagher-Fadel, M.K., Courgeon, S., Berthod, C., Ruffet, G., Bachèlery, P., Grenard-Grand, E., 2020. Evolution of the Glorieuses seamount in the SW Indian Ocean and surrounding deep Somali Basin since the Cretaceous. *Mar. Geol.*, 427, 106202. https://doi.org/10.1016/j.margeo.2020.106202.

Loncarevic, B.D., 1963. Geophysical studies in the Indian Ocean. *Endeavour*, 22, 43-47.

Mart, Y., 1988. The tectonic setting of the Seychelles, Mascarene and Amirante plateaus in the western equatorial Indian Ocean. *Mar. Geol*, 79(3–4), 261-274. https://doi.org/10.1016/0025-3227(88)90042-4.

Mathew, S.A., Nethaji Mariappan, V.E., 2014. Wind Resource Land Mapping using ArcGIS, WAsP and Multi Criteria Decision Analysis (MCDA). *Energy Procedia*, 52, 666–675. https://doi.org/10.1016/j.egypro.2014.07.123.

Matthews, D.H., Davies, D., 1966. A discussion concerning the floor of the northwest Indian Ocean – Geophysical studies of the Seychelles Bank. *Philos. Trans. Royal Soc. A*, 259(1099), 227-239.

Matthews, D.H., Vine, F.C., Cann, J.R., 1965. Geology of an area of the Carlsberg ridge, Indian Ocean. *Geol. Soc. Am. Bull.*, 76:675–682. https://doi.org/10.1130/0016-7606(1965)76[675:GOAAOT]2.0.CO;2.

Matthews, D.H., Davies, D., 1960. Geophysical studies of the Seyshells. *Philos. Trans. Royal Soc. A*, 259, 227-239. https://www.jstor.org/stable/73288.

McKenzie, D.P., Sclater, J.C., 1973. The evolution of the Indian Ocean. *Scientific American*, 228(5), 62–72. https://www.scientificamerican.com/article/the-evolution-of-the-indian-ocean/.

Mortimer, E.J., Gouiza, M., Paton, D.A., Stanca, R., Rodriguez, K., Hodgson, N., Hussein, A.A., 2020. Architecture of a magma poor passive margin – Insights from the Somali margin. *Mar. Geol.*, 428, 106269. https://doi.org/10.1016/j.margeo.2020.106269.

Murton, B.J., Rona, P.A., 2015. Carlsberg Ridge and Mid-Atlantic Ridge: Comparison of slow spreading centre analogues. *Deep-Sea Res. II: Top. Stud. Oceanogr.*, 121, 71–84. https://doi.org/10.1016/j.dsr2.2015.04.021.

Nonn, C., Leroy, S., Lescanne, M., Castilla, R., 2019. Central Gulf of Aden conjugate margins (Yemen-Somalia): Tectono-sedimentary and magmatism evolution in hybrid-type margins. *Mar. Pet. Geol.*, 105, 100–123. https://doi.org/10.1016/j.marpetgeo.2018.11.053.

Owen-Smith, T.M., Ashwal, L.D., Torsvik, T.H., Ganerød, M., Nebel, O., Webb, S.J., Werner, S.C., 2013. Seychelles alkaline suite records the culmination of Deccan Traps continental flood volcanism. *Lithos*, 182–183, 33-47. https://doi.org/10.1016/j.lithos.2013.09.011.

Pavlis, N.K., Holmes, S.A., Kenyon, S.C., Factor, J.K., 2012, The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *J. Geophys. Res.*, 117, B04406. https://doi.org/10.1029/2011JB008916.

Rapolla, A., Cella, F., Dorre, A.S., 1995. Gravity study of the crustal structures of Somalia along International Lithosphere Program geotransects. *J. African Earth Sci.*, 20(3–4), 263-274. https://doi.org/10.1016/0899-5362(95)00053-V.

Roonwal, G.S., 1986. *Origin and Development of the Indian Ocean*. In: The Indian Ocean: Exploitable Mineral and Petroleum Resources. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-95501-3_2.

Saha, A., Sensarma, S., Hazra, A., Ganguly, S., Peketi, A., Doley, B., Mudholkar, A.V., 2020. Imprints of ancient recycled oceanic lithosphere in heterogeneous Indian Ocean mantle: Evidence from petrogenesis of Carlsberg ridge basalts from Northwest Indian Ocean. *Gondwana Res.*, 86, 60-82. https://doi.org/10.1016/j.gr.2020.05.003.

Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E., Francis, R., 2014. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science*, 346(6205), 65-67. https://doi.org/10.1126/science.1258213.

Schott, W., Branson, J.C., Thurpie, A., 1975. Petroleum potential of the deep-water regions of the Indian Ocean. *Proceeding of the 9th World Petroleum Congress*, 2, 319-335.

Singh, R. P., Rawat, S., Chandra, K., 1999. Hydrocarbon potential in Indian deep waters. *Explor. Geophys.*, 30(1-2), 83-95. https://doi.org/10.1071/EG999083.

Singh, A.D., Conan, S.M.-H., 2008. Aragonite pteropod flux to the Somali Basin, NW Arabian Sea. *Deep Sea Res. Part I Oceanogr. Res. Pap.*, 55(5), 661-669. https://doi.org/10.1016/j.dsr.2008.02.008.

Smith, W.H.F., 1993. On the accuracy of digital bathymetric data. *J. Geophys. Res.*, 98(B6), 9591–9603. https://doi.org/10.1029/93JB00716.

Sreejith, K.M., Chaubey, A.K., Mishra, A., Kumar, S., Rajawat, A.S., 2016. Pseudofaults and associated seamounts in the conjugate Arabian and Eastern Somali basins, NW Indian Ocean – New constraints from high-resolution satellite-derived gravity data. *J. Asian Earth Sci.*, 131, 1-11. https://doi.org/10.1016/j.jseaes.2016.09.002.

Straume, E.O., Gaina, C., Medvedev, S., Hochmuth, K., Gohl, K., Whittaker, J.M., Abdul Fattah, R., Doornenbal, J.C., Hopper, J.R., 2019. GlobSed: Updated total sediment thickness in the world's oceans. *Geochem., Geophys., Geosystems*, 20(4), 1756-1772. https://doi.org/10.1029/2018GC008115.

Sumaila, U.R., Bawumia, M., 2014. Fisheries, ecosystem justice and piracy: A case study of Somalia. *Fisheries Research*, 157, 154-163. https://doi.org/10.1016/j.fishres.2014.04.009.

Torsvik, T.H., Ashwal, L.D., Tucker, R.D., Eide, E.A. 2001. Neoproterozoic geochronology and palaeogeography of the Seychelles microcontinent: the India link. *Precambrian Res.*, 110(1–4), 47–59. https://doi.org/10.1016/S0301-9268(01)00180-2.

Trott, C.B., Subrahmanyam, B., Murty, V.S.N., 2017. Variability of the Somali Current and eddies during the southwest monsoon regimes. *Dyn. Atmospheres Oceans*, 79, 43-55. https://doi.org/10.1016/j.dynatmoce.2017.07.002.

Wessel, P., Smith, W.H.F., 1991. Free software helps map and display data. *Eos Trans. AGU*, 72(41), 441. https://doi.org/10.1029/90EO00319.

Wessel, P., Smith, W.H.F., 1996. A Global Self-consistent, Hierarchical, High-resolution Shoreline Database. *J. Geophys. Res.*, 101, 8741-8743. https://doi.org/10.1029/96JB00104.

Wessel, P., Smith, W.H.F., Scharroo, R., Luis, J.F., Wobbe, F., 2013. Generic mapping tools: Improved version released. *Eos Trans. AGU*, 94(45), 409-410. https://doi.org/10.1002/2013EO450001.

Wessel, P., Luis, J. F., Uieda, L., Scharroo, R., Wobbe, F., Smith, W. H. F., Tian, D., 2019. The Generic Mapping Tools version 6. *Geochem. Geophys. Geosystems*, 20(11), 5556-5564. https://doi.org/10.1029/2019GC008515.

Woodroffe, S.A., Long, A.J., Milne, G.A., Bryant, C.L., Thomas, A.L., 2015. New constraints on late Holocene eustatic sea-level changes from Mahé, Seychelles. *Quat. Sci. Rev.* 115: 1-16. https://doi.org/10.1016/j.quascirev.2015.02.011.

Zonneveld, K.A.F., Brummer, G.A., 2000. (Palaeo-)ecological significance, transport and preservation of organic-walled dinoflagellate cysts in the Somali Basin, NW Arabian Sea. *Deep-Sea Res. II: Top. Stud. Oceanogr.*, 47(9–11), 2229-2256. https://doi.org/10.1016/S0967-0645(00)00023-0.