SEISMICITY IN YEMEN AND THE GULF OF ADEN IN A GEOLOGICAL CONTEXT

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Abstract. Seismicity in Yemen and the Gulf of Aden in a geological context. The study presents geologic investigation of Yemen and the Gulf of Aden with a special focus on geophysical, seismic, tectonic and topographic mapping performed by the integrated approach of QGIS and GMT scripting. Cartographic visualization is crucial in geologic analysis, data processing and prognosis of mineral resource prospects. The region of Yemen and Gulf of Aden was formed as a result of Arabian and African plates movements and still tectonically active. Besides, the Gulf of Aden contains mineral resources of hydrocarbons which makes this region actual for investigation. The IRIS database on earthquakes was used for visualization of the magnitude of submarine earthquakes in the Gulf of Aden for the period of 2007-2020. The paper presents 6 new thematic maps for the region of Yemen and Gulf of Aden. The research presented an analysis of correlation between the geological, topographic and geophysical settings. Through combined approach of cartographic high-resolution data visualization and geologic analysis, this paper contributed to the regional geological studies of Yemen, Gulf of Aden and the Middle East.

Keywords: Yemen, shell script, seismicity, earthquakes, geology, GMT

1. INTRODUCTION

The aim of this paper is to present an investigation of the geophysical and seismic setting in Yemen and the Gulf of Aden formed in the context of regional geological evolution and topographic structure. The methodology involves a data-driven mixed-tools cartographic method for integrated thematic mapping. The integrative cartographic approach was identified as a main technical focus of the present research, which presents the developed method the combined use of GMT and QGIS for geophysical and geological studies. Specifically, this includes a GIS-based mapping of the geology of Yemen by QGIS and a scripting iterative approach of the GMT for mapping geophysical fields (gravity, geoid), seismicity

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(earthquakes magnitude and location) and topography of Yemen and the Gulf of Aden.

The study captures an approach to synthesizing multiple vector and raster datasets (topography, geology, geophysics, seismicity) comparatively processed by the cartographic techniques of GIS and GMT. The datasets were derived from the open thematic sources on topography, geophysics and geology covering the region of Yemen and the Gulf of Aden, north-west Indian Ocean, Arabian Sea. The coordinates of the study area are 42°–55°E, 10°–20°N (Figure 1). Besides the cartographic visualization, the study is supported by the literature review for comprehensive understanding of the regional geological and tectonic processes.

2. GEOLOGICAL CONTEXT

The Gulf of Aden located southward of Yemen is a part of an extensive rift system that also includes the Red Sea, the Sheba Ridge (north of Socotra Island), the Afar region (Northeastern Ethiopia and Djibouti), two gulfs of the Sinai Peninsula (the Gulf of Aqaba, the Gulf of Suez), and the Cairo basalt province (*Bosworth et al. 2005*). The oceanic spreading centre Gulf of Aden-Ethiopian Rift Afar-Red Sea extends at 2,800 km from the Carlsberg Ridge to ca. 19°N in the Red Sea (Mohr, 1970), geometrically presenting the Afro-Arabian triple junction in the rift system (Baker et al. 1996).

The geologic evolution of Yemen is strongly affected by the tectonic movements of the Arabian and African plates. The collision between the Eurasian and Arabian tectonic plates triggered the movement of the Arabian plate in N-NE direction, across the Gulf of Aden and Red Sea basins (Khan, 1975; Beydoun et al. 1996). This process in turn initiated the continental rifting because of the active mantle upwelling. Continental rifting began in the Gulf of Aden by ~29.9 to 28.7 Ma. Spreading through most of the eastern Gulf of Aden took place in the Miocene (~10 Ma) (McKenzie et al. 1970) and <ca.5 million years age in the western Gulf of Aden, Afar and the southern/central Red Sea. The main phase of the deep axial subsidence and ocean-water inundation in the Gulf of Aden commenced in the late middle Oligocene to Miocene, and resulted in deposition of thick marine mudstones and deep water carbonates (Bosworth, 2015).

The Gulf of Aden experienced lateral propagation of the axial oceanic spreading centers in its rift system which initiated over 19 M years and still continues (Beydoun and Sikander, 1992), which makes the area tectonically active. Such tectonic and geologic complexity is reflected in the presence of mineral resources. For instance, the hydrocarbons were identified in deep geological structures of in Tawila oil field reservoirs in the Masila rift basin of Yemen (Bosworth and Burke, 2005) and Jurassic Meem Shale Member is widely exposed within the Sabatayn Basin, and the Al-Jawf sub-basin (Al-Johi et al. 2019) which presents prospectives in petroleum exploration of the region. The area of Yemen is mainly covered by stratified volcanic rocks of Tertiary age (Arnous et al. 2020), as can be seen in Figure 3 (bright magenta color).

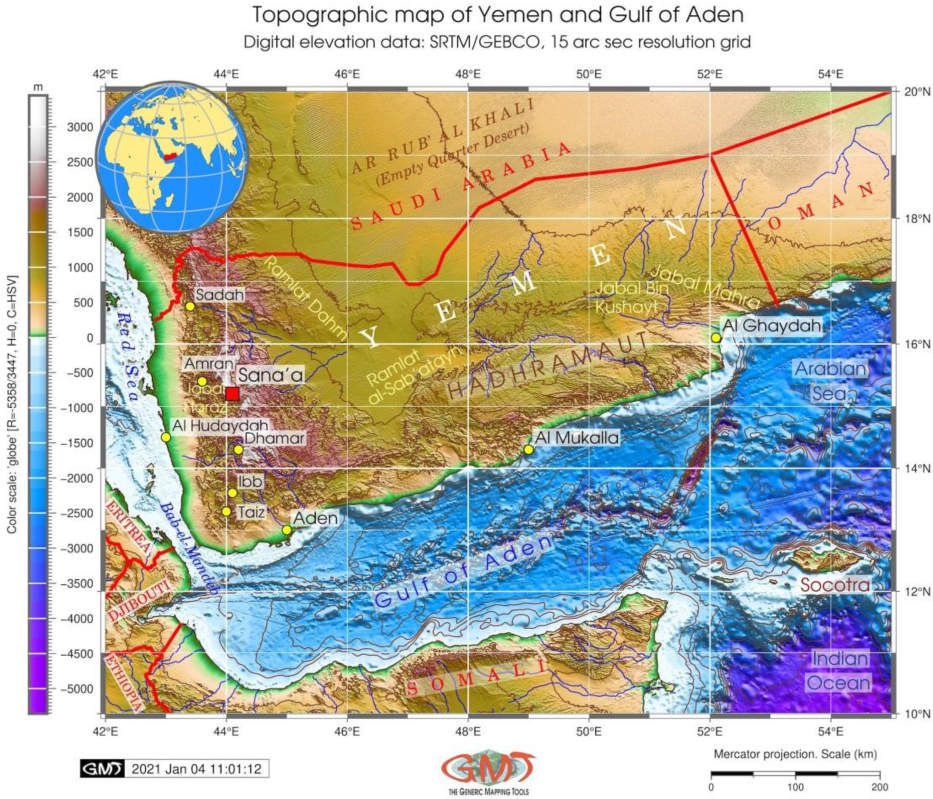

Fig. 1. Topographic map of Yemen. Data: GEBCO. Mapping: GMT. Source: author.

The rift orientation has generally an oblique direction (Figure 4), because of the passive lithospheric necking of the Arabia-Somalia plate along the section between Socotra and the Red Sea-Ethiopian rift. However, some individual segments of ridge are oriented quasi-perpendicular to the plate motion, similar to the lithospheric cracks (Hakimi et al. 2019). Despite the existing works reporting new highlights on Yemen geology (Beydoun, 1966; Redfern and Jones, 1995) and geomorphology many segments are still enigmatic.

For example, the Qamar rift basin, located in eastern Yemen, adjacent to the Indian Ocean Rift, was formed as a result of rift reactivation during the mid Cretaceous. The nature of the pre mid-Cretaceous basin fill of this area is still unknown and require additional studies (Brannan et al. 1997). Having an area of continental shelf over 40,600 km2, the Gulf of Aden presents a geologically perspective exploration area, because the tectonic anticlines serve as primary structure traps associated with faults where clastic reservoirs exist in Oligocene sub-basin, as shown by the syn-rift exploration (Bott et al. 1992). The importance of integrating geochemical data analysis in the Gulf of Aden into reconstructing of the tectonic evolution and analysis of volcanism and seismic activity has been supported by existing studies (Baker et al. 1994; Zumbo et al. 1995).

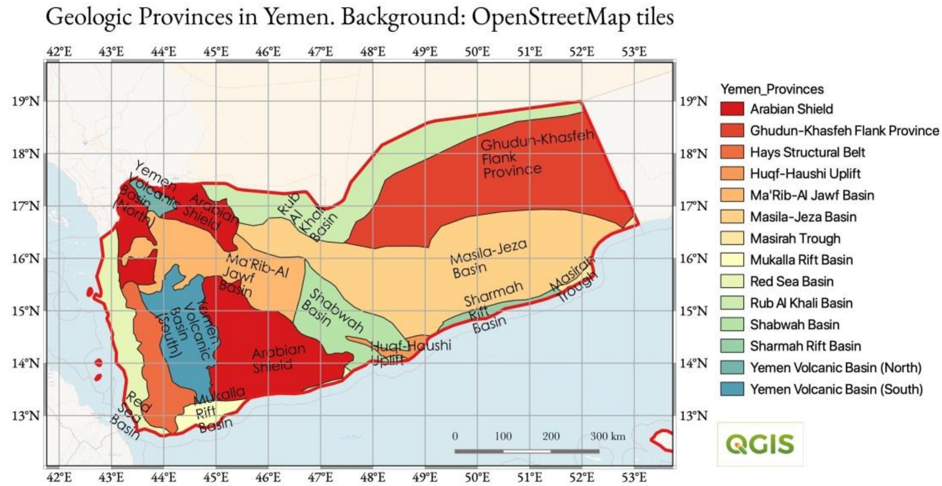

Fig. 2. Geologic provinces in Yemen. Data: USGS. Mapping: QGIS. Source: author.

Landscapes and geomorphic landforms in Yemen have a complex origin and formed under varied hydrological and climate factors during Holocene (El Bastawesy, 2015; Davies, 2006; Lezine et al. 1998). The deep correlations between the factors of climate and hydrology, ocean circulation, glaciation and geology, sedimentary processes and geomorphology, tectonics and geodynamics are well described in the existing studies (Kuhn et al. 2006; Lemenkova, 2020a, 2020b; Gohl et al. 2006). In brief, the landscapes of Yemen can be divided into the following types: the coastal plains in the west and south-west, the central highlands (an extensive high plateau over 2,000 m according to the topographic data), the Ar-Rub' al Khali Desert in the east and north-east and the Hadhramaut Mountains (Jibāl Al-Mahrah) in the south (Figure 1). The hydrology of the country is notable for numerous lagoons, makes it marshy in spite of the arid climate. The lakes formed during Holocene under special climate and geologic setting.

3. MATERIALS AND METHODS

3.1. Data Capture

By extracting data from publicly available open repositories, this research presents a synthesized geospatial project on geology, seismicity, tectonics, geophysics and topography of Yemen including vector polygons (SHP files in ArcGIS format) and raster grids (GRD, IMG and NetCDF formats). Specifically, the data include GEBCO/SRTM topographic grid (https://www.gebco.net/) (Schenke, 2016), EGM-2008 geoid model (Pavlis et al. 2012), gravity satellite derived grids (Sandwell et al. 2014), geologic datasets from the USGS (Pollastro et al. 1999). The seismic data with information on earthquakes were captured through the IRIS Wilber 3 system (https://ds.iris.edu/wilber3/). The data were processed by the GMT and QGIS. With these datasets, this study performed a series of the thematic maps to cartographically visualize new maps and to assess if the topographic, geophysical and geological setting affect the earthquakes distribution over the Gulf of Aden.

3.2. GMT Scripting

Nowadays, applying methods of automatic data processing in cartography is academically acknowledged (Lemenkova, 2019a, 2020c, 2020d; Gauger et al. 2007; Schenke and Lemenkova, 2008). The Generic Mapping Tools (GMT) (Wessel et al. 2019) is a scripting cartographic toolset developed by Paul Wessel and Walter H. F. Smith. The GMT-based scripting-oriented approach, compared to the traditional mapping, provides a response to the need for machine learning cartographic development in Earth sciences aimed at quick, accurate and precise processing of the large datasets (raster grids, tables, vectors layers) with as least as possible handmade routine. The GMT was used by existing method [Lemenkova, 2019b, 2020e] for plotting maps in Figures 1, 4, 5 and 6 showing topography, seismic, tectonic and geophysical setting (geoid and gravity), respectively.

The conceptual process of mapping by GMT involved writing scripts for plotting maps which include following important steps: a) creating a subset of the study area by the coordinates (in this case: -R42/55/10/20) and projecting (in this case: Mercator projection with map extent at 16.5 cm, set up by '-JM6.5i' function); b) visualizing raster grids; iii) adding cartographic elements on maps using methodological approach of GMT by modular system; iv) integrating lines of code in a script and running it from the console; v) visualizing map and converting it to the graphical format; vi) performing analysis of the cartographic results. Among others, the most important GMT modules used in this study include ‘grdcut’, ‘grdimage’, ‘grdcontour’, ‘psbasemap’, ‘pscoast’, ‘pstext’, as the key modules.

3.3. QGIS Mapping

The QGIS (QGIS.org, 2020) part of research assembled two geologic datasets (Figure 2 and Figure 3) for use in geologic visualization and analysis.

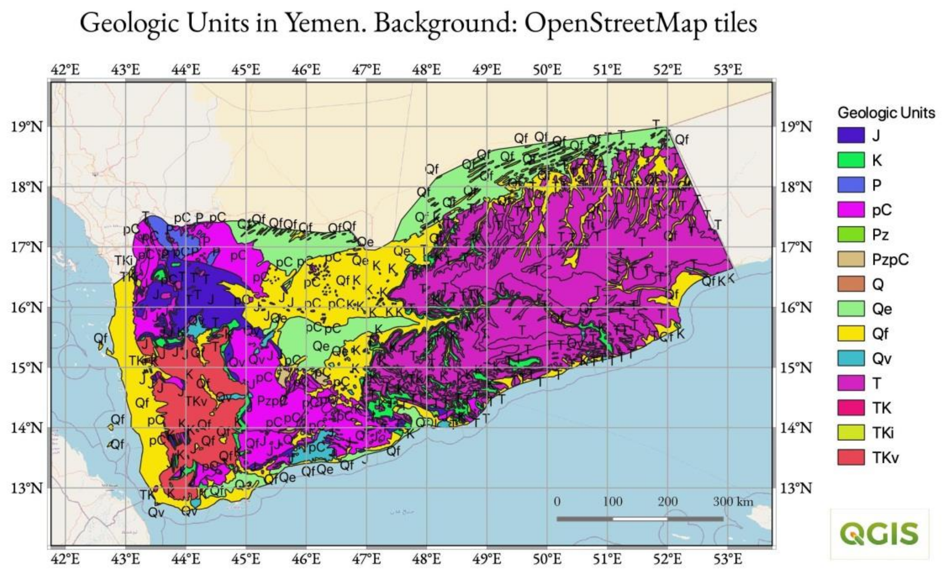

Fig. 3. Geologic Units, Volcanics and Intrusives in Yemen. Data: USGS. Mapping: QGIS. Source: author.

QGIS is a free open source GIS, generally compatible with the shape file formats and widely used in geoscience as a background GIS for further statistical data analysis (Lemenkova, 2018b, 2019c), One is including geological provinces fo Yemen (visualized in Figure 2) which had a sequence of basins, the Huqf-Haushi Uplift (coastal area of the Gulf of Aden) and Ghudun-Khasfeh Flank Province bordering the Oman (Figure 2).

The other dataset integrates the geological units in the region of Yemen (visualized in Figure 3). For this one, the map visualizes geologic units of Yemen from several epochs such as Jurassic (J), Quaternary (Q), Quaternary eolian (Qe), Quaternary fluvial (Qf), Quaternary volcanics (Qv) Cretaceous (K), Paleozoic (Pz), Paleozoic Precambrian (PzpC), Precambrian undifferentiated (pC). The Tertiary unit is sub-divided into the Tertiary (T), Tertiary Cretaceous (TK), Tertiary Cretaceous intrusives (TKi), and Tertiary Cretaceous volcanics (Tkv). The vector layers have been obtained from the USGS, each polygon visualized by random colors using the categorical palette in QGIS.

4. RESULTS AND DISCUSSION

Figure 1 shows the topographic map of Yemen and surrounding Gulf of Aden, which ranges according to GEBCO grid from -5358 m to a maximum of 3447 m. The maps shows isolines plotted every 500 m taken from the ETOPO1 grid for generalization purpose. The topography of the region shows variations in the elevations with a notable landforms of Hadhramaut, a dominant structure related to Oligo-Miocene rifting of the development of the Gulf of Aden. Other notable topographic elements include, among others, Jabal Bin Kushayt, Jabal Mahra and Ramlat al-Sab'atayn, among other. The latter suites of dunes continues to the Rub' al-Khālī (Empty Quarter).

Figure 2 shows the geologic provinces in Yemen. The Masila-Jeza Basin and Shabwah Basin on the south-east (beige and green colours in map of Figure 2) present a special interest, since they are the only hydrocarbon-producing Mesozoic basins in Yemen, with detected rocks with high organic carbon content and burial thermal maturity. Among other areas the map visualizes the continuation of the Arabian Shield near the Ramlat Dahm sand area.

Figure 3 shows the geologic units in Yemen. The dominating units are Quaternary (Q) visible in the eolian units (Qe) in north, and fluvial (Qf) units in the coastal areas along the Red Sea and in the central parts of the country (Ramlat al-Sab'atayn). The region of Yemen still remains tectonically active with recorded earthquakes, which is expressed in the presence of Quaternary volcanics (Qv) in the southern regions of the country (Aden area). The Cretaceous (K) are found only occasionally in the fragmentary regions on the south and the north-west. The Tertiary unit (T) occupies the north-east region of the country and includes the Early Tertiary volcanic rocks, formed during rifting and pre-rift sedimentary rocks.

Figure 4 shows the seismicity of the region demonstrating the earthquakes magnitude. The data were gathered from the IRIS at different levels of aggregation, for a Yemen as a whole as well as for an area of the Gulf of Aden, visualizing earthquake magnitudes by colours for the years 2013 to 2020 (last 7 years coverage) taken from the IRIS dataset. Since all the data show shallow volcanoes (less than 10 km), the depth has been ignored in the visualization parameters. Selected tectonic elements, such as fracture zones, tectonic slab contours, extent of the large igneous provinces, locations of volcanoes and faults are plotted additionally to visualize the geologic setting in the region of the Gulf of Aden.

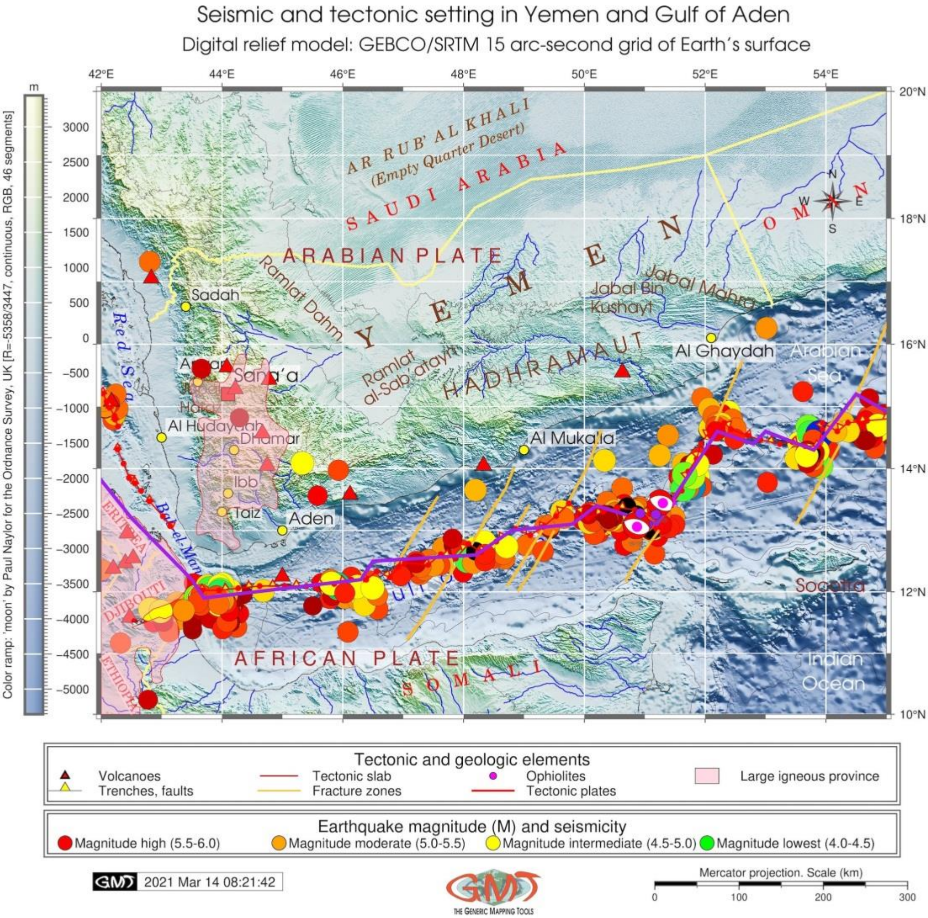

Fig. 4. Earthquakes seismicity in the Gulf of Aden and Yemen. Data: IRIS. Mapping: GMT. Source: author.

Figure 5 shows the geoid undulations over the study area of Yemen. The variations in values (from -50 to 3 m) are caused by the by the heterogeneity of the lithosphere, lower mantle, upper mantle and lithosphere, thus reflecting the rock density anomalies, as well as current tectonic plate motion, deformation and stability. The geoid undulations in Yemen is the result of a time-space dynamical equilibrium with a complex mechanism that includes the sum of spherical harmonics of the lateral Earth's rocks density heterogeneity.

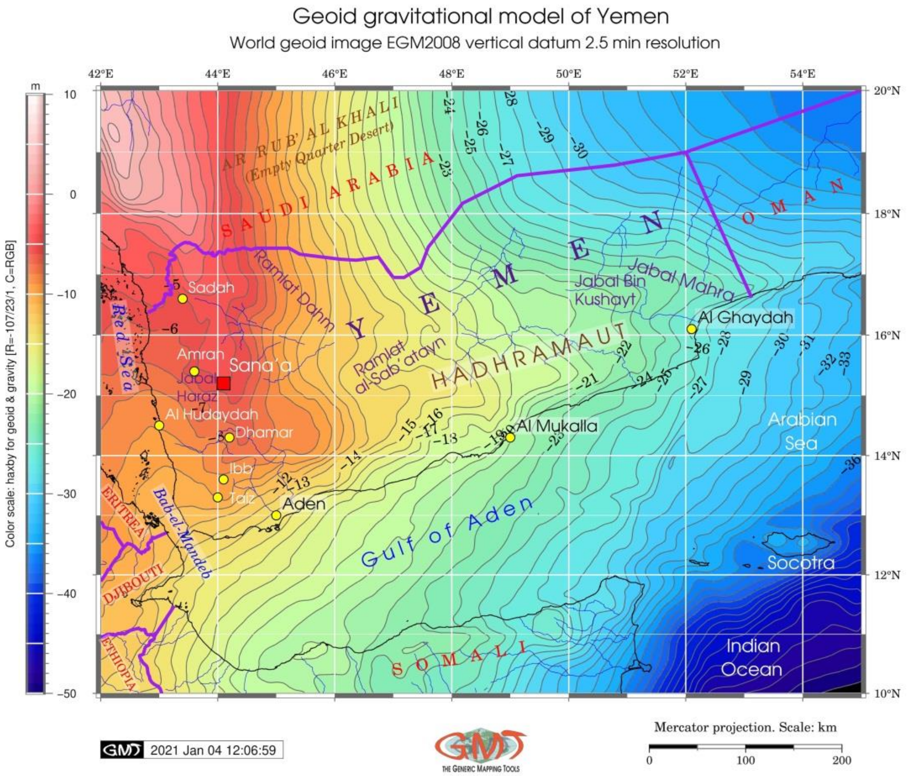

Fig. 5. Geoid model of Yemen and Gulf of Aden. Data: EGM-2008. Mapping: GMT. Source: author.

Figure 6 shows the free-air gravity in Yemen and the Gulf of Aden. Spatial variability of the gravity field (range: from -139/286 mGal), the signal shows variable rock density over Yemen and the Gulf of Aden, which causes changes in the gravity field. By the comparing of the topographic map (Figure 1) with the free-air gravity variations (Figure 6), the correlations between the isolines reflect correlations between the density and actual gravity values. As a result of this study, the multi-source data were collected in the open repositories to visualize geologic structure, topographic variability, seismicity and geophysical dynamics in Yemen and the Gulf of Aden and investigate the evolution based on the literature analysis.

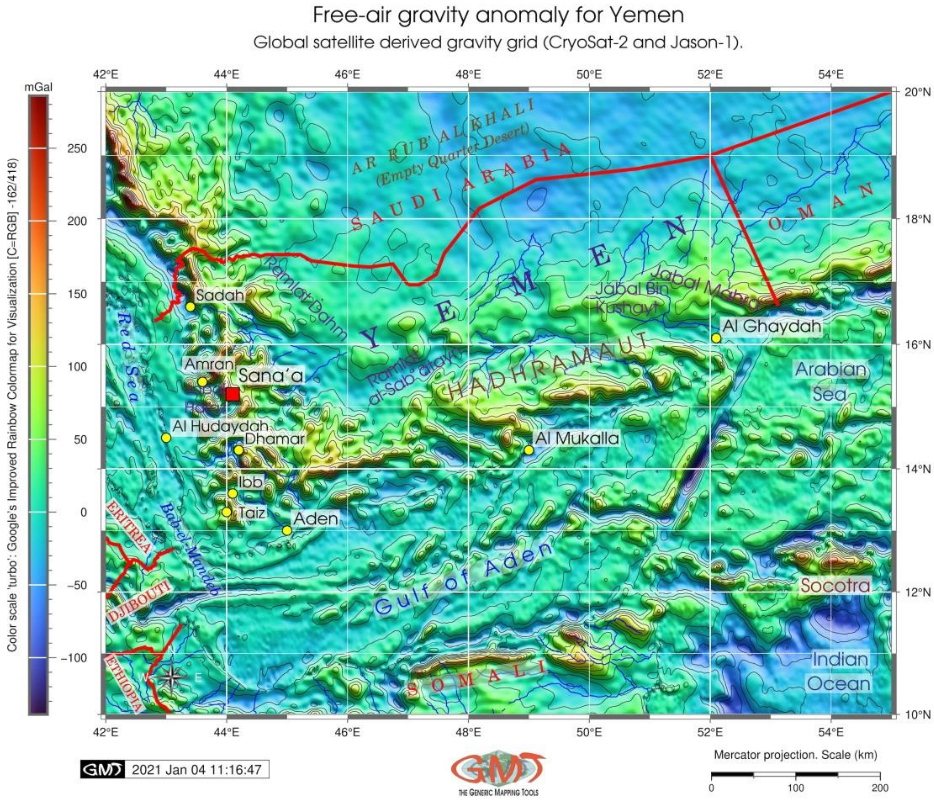

Fig. 6. Gravity in Yemen and Gulf of Aden. Data: CryoSat-2, Jason-2. Mapping: GMT. Source: author.

The integrated data analysis is an effective tools presented and reported in various publications and proved in this study. For instance, the combined use of topographic, tectonic and bathymetric maps (Manighetti et al. 1997), geophysical and geological data (Lemenkova, 2021a, 2021b), aeromagnetic data processed by GIS (Al-Badani and Al-Wathaf, 2018), vector layers and statistical data (Klaučo et al. 2013a, 2013b), seismic, gravity and magnetic data combined with results of structural geology (Rihm and Henke, 1998), engineering geological plotting (Lemenkov and Lemenkova, 2021), environmental mapping (Suetova et al. 2005) to mention a few approaches.

CONCLUSIONS

The tectonics in the Rift Basins of the Gulf of Aden, its lithology and geologic evolution is presented in other studies that details its setting and complex correlation between various factors and phenomena (Bosence et al. 1998; Hughes and Beydoun, 1992; Le Pichon, and Francheteau, 1978). Despite thorough analysis and theoretical investigations presented in these and other relevant works, the need for the updated maps based on the high-resolution datasets is always a challenge in the geological studies. In this context, this study contributes to the datasets of the existing maps on Yemen through the presented six new maps showing the spatial setting in the region and demonstrating correlation between the geology, topography and seismicity of the Gulf of Aden.

The integrated scripting cartographic framework by application of GMT has until now been developed in a quite narrow research context of the geophysical mapping of the oceanic deep-sea trenches (Lemenkova, 2021c, 2018). This study concludes that the geologic and geophysical factors affecting the distribution of the major earthquakes well correlate with the tectonic settings which was visualized on the maps and visible upon comparative analysis of the presented thematic maps. Based on the cartographic presentation, it can be proposed for future research that the combined use of GIS and scripting (presented by the QGIS and GMT) is a perspective mapping approach that enables to effectively visualize raster and vector layers for complex data analysis from the multiple sources.

The recommendation for further similar works includes linking various plugins to the QGIS, application of R and Python for graphical plotting, adding other datasets (e.g. for plotting stratigraphic columns or statistical graphics). Future development and deepen of the geologic investigations in Yemen would ideally need to include a fieldwork for mineral resource exploration extending into the Gulf of Aden. It is also recommended to use other GMT modules, apply GRASS GIS for satellite image processing (e.g. Sentinel-2A), to extend cartographic analysis of the geology of Yemen to engage with integrated data-driven mode of the mapping framework for regional geologic analysis of the Middle East.

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