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## ► To cite this version:

Polina Lemenkova. Mesopotamia Foredeep Basin Mapped by Integrated 2D and 3D Cartographic Approach for Analysis of the Geomorphology and Geophysical Setting. Iraqi Bulletin of Geology and Mining, 2021, 17 (2), pp.57-76. hal-03466375

**HAL Id: hal-03466375**

**<https://hal.science/hal-03466375>**

Submitted on 5 Dec 2021

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## **MESOPOTAMIA FOREDEEP BASIN MAPPED BY INTEGRATED 2D AND 3D CARTOGRAPHIC APPROACH FOR ANALYSIS OF THE GEOMORPHOLOGY AND GEOPHYSICAL SETTING**

**Polina Lemenkova**

Received: 03/ 01/ 2021, Accepted: 03/ 07/ 2021

Keywords: Iraq; Mesopotamia; Gravity; Geomorphology; GMT; QGIS Mapping

### **ABSTRACT**

The study presents the 2D and 3D mapping of the Mesopotamia Foredeep Basin, Iraq, and the adjacent areas using integrated cartographic approach of multi-source data visualization by Generic Mapping Tools (GMT), R language and QGIS. The geomorphological and geological mapping is based on multiple datasets containing raster and vector layers of the geological, geophysical, topographic, lithological and geodetic data captured from the open source repositories and resulted in 8 new maps. This study develops and presents an integrated cartographic method combining the use of various tools for different tasks in data visualization: QGIS for geological mapping, GMT for mapping geoid, gravity anomalies, 3D mesh visualization and 2D topographic mapping, R language (libraries 'raster' and 'tmap') for modelling relief (slope and aspect) of Iraq. The topography shows variation in data from minimum at -69 m below sea level in the Arabian Gulf, to maximum at 3754 m asl in the NE of Iraq. The map of geologic units of Iraq shows dominating types are Quaternary (Q) and Tertiary (T) that roughly divide the country into two segments (SW and NE). The Mesopotamia Foredeep Basin is dominated by Quaternary (Q). The 3D model of the Iraqi relief presented perspective view of the Mesopotamia Foredeep Basin and Zagros Mts with azimuth rotation at 165°/30°. The geoid undulations increase in NW direction: the lowest, negative values of geoid (-17 m) are over the Arabian Gulf which reflects the continuum of the Indian geopotential minimum. Maximal values of geoid reach 19 m in the SW and NW. The Mesopotamia Foredeep Basin has geoid variations ranging from -15 to 5 m showing correlation with topographic depressions. Free-air gravity model shows correlation of the values with topography proving general trend of the deficit of landmasses causing the negative or lower values in gravity. The values of Faye's gravity anomalies differ from minimum at -124.945 mGal to maximum at 327.724 mGal. The Mesopotamia Foredeep Basin has clearly negative values. The generated cartographic outputs (8 new maps) contribute to the increase of knowledge on the geomorphology, geology and distribution of geophysical anomalies of Iraq with a special focus on Mesopotamia Foredeep Basin. The technical research questions covered by this study relate to the cartographic data formatting, processing, integration and modelling using thematic multi-source datasets covering Iraq. The paper contributes both to the cartographic aspect of integrated mapping and to the regional studies of Iraq, Middle East and the Mesopotamia Foredeep Basin.

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## تحليل الوضع الجيومورفولوجي والجيوفيزيائي لحوض ما بين النهرين من خلال تكامل خرائط ثنائية الأبعاد وثلاثية الأبعاد

بولينا ليمينكوفا

### المستخلص

تم في هذه الدراسة اعداد خرائط ثنائية الأبعاد وثلاثية الأبعاد لحوض ما بين النهرين في العراق والمناطق المجاورة من. خلال تكامل لبيانات متعددة المصادر بواسطة لغة برمجة GMT و R و QGIS. اعتمد رسم الخرائط الجيومورفولوجية والجيولوجية على مجموعات البيانات التي تحتوي على طبقات نقطية وموجهة للبيانات الجيولوجية والجيوفيزيائية والطوبوغرافية والصخرية والجيوديسية التي تم جمعها من مستودعات مفتوحة المصدر. تتضمن النتائج 8 خرائط جديدة. تقدم هذه الدراسة طريقة رسم خرائط متكاملة تجمع بين أدوات مختلفة لتصوير البيانات: QGIS لرسم الخرائط الجيولوجية، GMT لتخطيط الجيود، شذوذ الجاذبية، التصوير ثلاثي الأبعاد ورسم الخرائط الطبوغرافية ثنائية الأبعاد، ولغة البرمجة R لنمذجة التضاريس الجيومورفولوجية لأراضي العراق. بينت الخريطة الطبوغرافية تباين في الارتفاع من -69 متر تحت مستوى سطح البحر في الخليج العربي الى 3754 متر فوق مستوى سطح البحر في الأجزاء الشمالية الشرقية من العراق. أظهرت الخريطة الجيولوجية ان ترسبات العصر الرباعي (Q) وترسبات العصر الثلاثي (T) هي الترسبات السائدة والتي تقسم العراق بشكل تقريبي الى جزئين (شمالي شرقي وجنوبي غربي). ترسبات العصر الرباعي (Q) هي الترسبات الغالبة التي تغطي حوض ما بين النهرين. قدم النموذج ثلاثي الأبعاد رسم منظوري لحوض ما بين النهرين وجبال زاكروس.

عند تدوير زاوية السميت بمقدار  $165^{\circ}/30^{\circ}$ . تزداد تموجات الجيود بالاتجاه الشمالي الشرقي: القيمة السالبة الأكثر انخفاضاً للجيود هي (-17 م) وكانت على امتداد الخليج العربي، وتعكس استمرارية الحد الأدنى للجغرافي الهندية. الحد الأعلى للجيود هو 19 في الاتجاه الجنوبي الغربي والشمالي الشرقي. يتباين ارتفاع الجيود في حوض ما بين النهرين من -15 م الى 5 م متوافقاً مع المنخفض الطبوغرافي. نموذج جاذبية الهواء الحر أظهر توافق بين قيم الجاذبية والتضاريس والتي تثبت الإتجاه العام لتناقص الكتلة التي تكون سبب لقيم الجاذبية المنخفضة أو السالبة. تختلف قيم انحرافات الجاذبية لـ Faye بين الحد الأدنى -124.945 ملي كال الى الحد الأعلى 327.724 ملي كال. من الواضح ان قيم الجاذبية في حوض ما بين النهرين هي قيم سالبة.

تساهم مخرجات رسم هذه الخرائط (8 خرائط جديدة) في زيادة المعرفة حول الجيومورفولوجيا والجيولوجيا والشذوذ الجيوفيزيائي في العراق مع التركيز على حوض - ما بين النهرين في العراق. تتعلق دراسة أسئلة البحث الفني بتنسيق البيانات الخرائطية ومعالجتها وتكاملها ونمذجتها بواسطة مجموعات بيانات إنشائية متعددة المصادر تغطي العراق. تساهم الورقة بالإضافة الى اعداد الخرائط في الدراسات التكاملية الإقليمية للعراق والشرق الأوسط وحوض ما بين النهرين.

## INTRODUCTION

### ■ Background

Regional geologic settings and tectonic evolution of Iraq (Fig.1) play the most important role in the development of its modern landforms and topographic patterns formed as a result of the complex interrelation of the geologic processes (Sissakian, 2013). Key processes of the geologic evolution and tectonic plate movements are connected with geomorphological structures of Iraq directly or indirectly (Ali *et al.*, 2014; Sissakian *et al.*, 2020a). The impact of the geologic process is especially important for the mountainous regions and highs of Iraqi Zagros Fold Belt, a seismically active orogen (Bretis *et al.*, 2011), Khlesia Uplift (Baban, 1983; Ali *et al.*, 2012; Berberian, 1995), Mesopotamian Foredeep Basin, rich in hydrocarbon resources, as reported in multiple publications (see e.g. Murris, 1980; Alsharhan and Nairn, 1997; Al-Ameri *et al.*, 2011; Al-Khafaji *et al.*, 2019; Al Atroshi *et al.*, 2020).

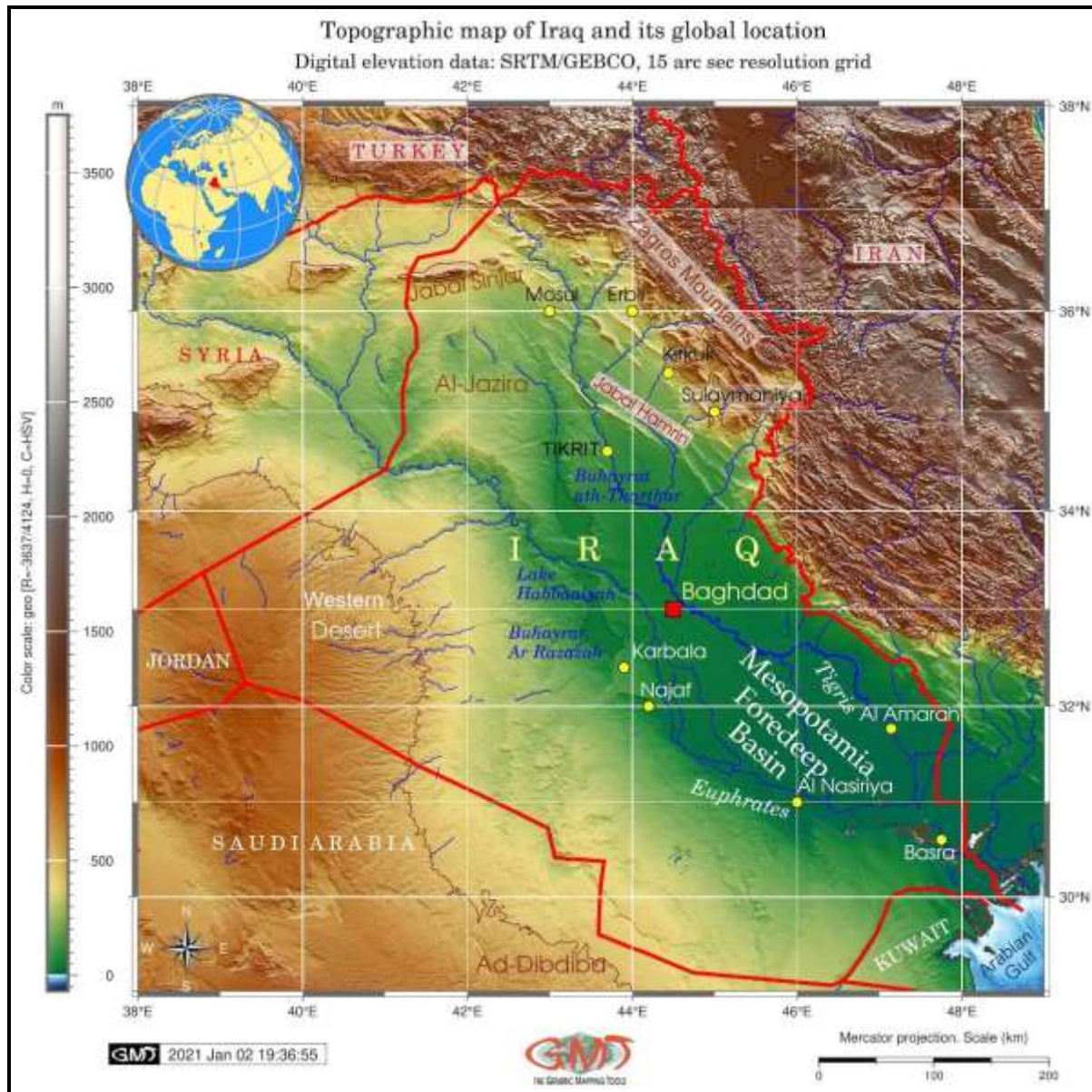


Fig.1: Topographic map of Iraq. Mapping: GMT

#### ■ Research aim and objectives

The aim of this study is analysis of the geomorphological, geological and geophysical variability in Iraq and a special focus on the Foredeep Mesopotamia Basin, technically achieved by the cartographic scripting approach. Geomorphology of Iraq draws its roots from the complexity of natural setting of the country that includes geology, tectonic processes, sediment accumulation in the landscapes, climate processes (aeolian processes and temperature) and hydrological factors (density of river network). The geomorphology of Iraq differs from neighbor countries in that its landforms present contrasting variability in its morphologically distinct regions: Mesopotamia Plain, deserts (both Southern and Western Desert) and Zagros Fold and Thrust Belt. Various factors affect the geomorphology of Iraq in a different way. For instance, the endogenous factors, such as tectonic movements and geologic evolution formed general large-scale landforms in the past, e.g. Zagros. The exogenous factors, such as aeolian or fluvial processes, continue shaping the relief in

moderate to minor scale until present time. These processes include erosion, transportation, accumulation and deposition of sediments across the surface of the landscapes in Iraq. Hence, the objective to achieve this goal consists in the thematic mapping which seeks to illustrate regional variability of these factors (geological, geophysical and topographic) in Iraq to illustrate the complexity of factors affecting the geomorphology of the country.

The objective of mapping was to include a series of maps incorporated high-resolution data into the cartographic modeling of Iraq by scripting workflow using Generic Mapping Tools (GMT) and R programming. The 3D approach of cartographic model was presented as a special objective of this study tested for interpretation that there is a distinct depression in the relief of the Mesopotamia Foredeep Basin well correlated with geologic accumulation of Quaternary sediments. The performed scripting-based mapping using R language presented a sub-series of maps and spatial statistics on variations of slope steepness, aspect orientation and DEM elevation heights modeled using 'raster' library of R programming. The visualized maps on geomorphometric variables of the Iraq corroborate the interpretation of relief pointing the contrasting geomorphology enabling to compare the Mesopotamia Plain with Zagros, while mapping thematic geophysical maps aimed to add information on the gravity distribution over the whole country.

#### ■ **Research gap identification**

The lack of the integrated cartographic visualization of Iraq based on using scripting approach and the discrepancy of this technical task with the complexity of the study area leads this study to reconsider an assumption concerning the asset of the advanced cartographic methods for geological studies. Indeed, the effective data visualization and modeling enables to find correlation between the non-linear processes in the Earth science through the geophysical, geological and tectonic processes reflected in current topographic shape of the Earth in general and such complex regions as Iraq in particular. In general approximation, the geomorphology of Iraq is largely influenced by geophysical, geological, climate (aeolian), and hydrological (fluvial) processes of sediment accumulation and denudation across the surface of the landscapes. Understanding the complexity of this correlation requires advanced cartographic solutions in data modelling achieved through scripting and multi-disciplinary approach of geological-cartographic data integration.

Therefore, to fill in the gap in the geological-cartographic multi-disciplinary studies of Iraq, this study presents the results from scripting-based mapping of the country in general and Mesopotamia Foredeep Basin in particular compared with Zagros Fold and Thrust Belt, including 2D and 3D data visualization, geomorphometric modeling and geologic interpretation of the presented maps. As a result, the presented investigations of Iraq using R, QGIS and GMT produced enhanced maps in raster and vector format made in traditional and automatic approaches of mapping. High-resolution data were used as input materials covering Iraq. Accurate visualization of the thematic data were achieved through both scripting and GIS-based approach from the multi-task approach. The scripting method of R and GMT, in contrast to QGIS, used a programming syntax which enabled to perform cartographic workflow in a faster and preciser machine-based approach. The proposed refinement of the integrated mapping of Iraq produced a series of new eight maps. Raster data were processed by R and GMT which included a high level of automation, while vector data were handled by QGIS that required more traditional GIS mapping routine.

Advanced cartographic algorithms and approaches are necessary to obtain reliable 2D and 3D maps in geological studies and geomorphometric analysis, especially in regions with

such contrasting diversity of landscapes as Iraq. Therefore, three methodological approaches (GMT, R and QGIS) were tested to present a set of maps covering study area. Automatic generation of maps using R and GMT scripts shown to be more sophisticated due to its modular and coding syntax. The QGIS method, in contrast, enables a more straightforward mapping by means of the traditional GIS menu which is based on more active user-controlled cartographic workflow, yet lesser degree of automatization compared to GMT and R. Both methods were applied and presented for mapping. Eight new maps have been plotted by the comparative methods of traditional and scripting cartography applied for geological, geomorphological, geophysical and topographic analysis of Iraq and Mesopotamia Plain as its geologically special region. The obtained results are promising in terms of mapping quality and geologic applicability, which is discussed in more details in the respective sections below.

#### ■ **Study area**

The geologic provinces of Iraq (Fig.2) include, following USGS classification codes: the Mesopotamian Foredeep Basin, Zagros Fold Belt, Widyan Basin, Wadi Surhan Basin, Rutbah Uplift, Khleisha Uplift, Hail Ga'ara Arch, Euphrates/Mardin and the Anah Graben. The Mesopotamian Foredeep Basin (lilac color in Fig.2) was formed during the continental collision of the Arabian Plate with the Eurasian Plate (Al-Kubaisi, 2014). It presents a narrow zone that extends generally in NW-SE direction, roughly parallel to the Zagros Mountains. It stretches from northern Iraq bordering with Khleisha Uplift (orchid color in Fig.2) to the Persian Gulf, boarded to the east by the Zagros Fold and Thrust Belt and to the west by the Interior Platform province. To the northwest, the basin converges with the Zagros Fold Belt, which extends along the Zagros Thrust Zone in both Iraq and Iran. The Mesopotamian Foredeep Basin plays a significant role in the generation of oil formation in Iraq which began ca. 250 million years ago, reaching peak generation during the Jurassic Period (Fox and Ahlbrandt, 2002). The geologic units within the study area of Iraq (Fig.3) include two clearly dominating units: Q (Quaternary) and T (Tertiary), visualized as red and lilac colors, respectively in Fig.3. These units roughly divide the whole country into two dominating parts, the western (Widyan Basin – Interior Platform) and eastern (Mesopotamia Foredeep basin and Zagros).

The Rutbah Uplift formation shows a mixed coverage by the J (Jurassic), K (Cretaceous) and Tr (Triassic) units. The Quaternary fluvial units (Qf) demonstrate occasional insertions in various fragments of the study area, as well as the Quaternary Tertiary (QT) mostly concentrated in the northern part of Iraq (Euphrates/ Mardin province) and Quaternary sabkha (marsh green colors) in the southern part of the country in the Mesopotamia Foredeep Basin.

The other types of geological units include Mesozoic Cenozoic intrusives and volcanos (MzCzi and MzCzv) fragmentary occurring in the northern border of Iraq. Various factors affect landforms and geomorphology of the region. Besides the tectonics, the geomorphology is deeply connected with global and regional climate fluctuations, sedimentation and geodynamic evolution during the past (Sadooni and Alsharhan, 2019; Gohl *et al.*, 2006a, 2006b; Lemenkova, 2020a; Kuhn *et al.*, 2006). An illustrative example of such a correlation is the Oligocene epoch which included a climatic change leading to the Antarctic glaciation, decrease in ocean water temperature, salinity, nutrient supply and sediment accumulation.

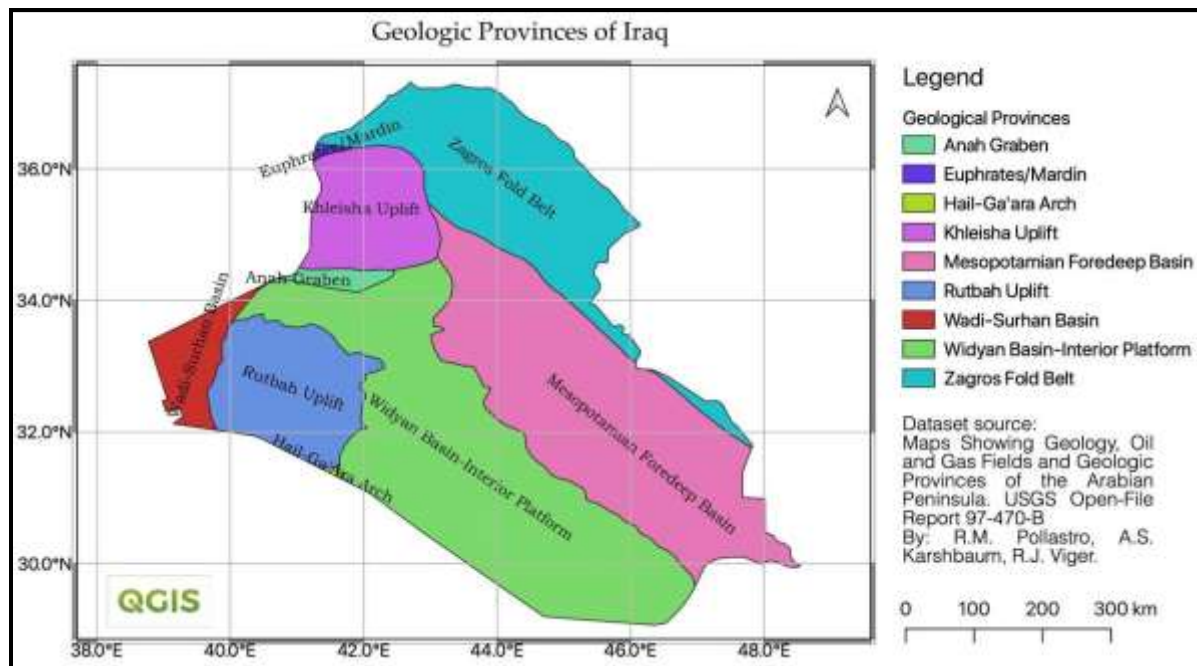


Fig.2: Geologic provinces map of Iraq. Mapping: QGIS

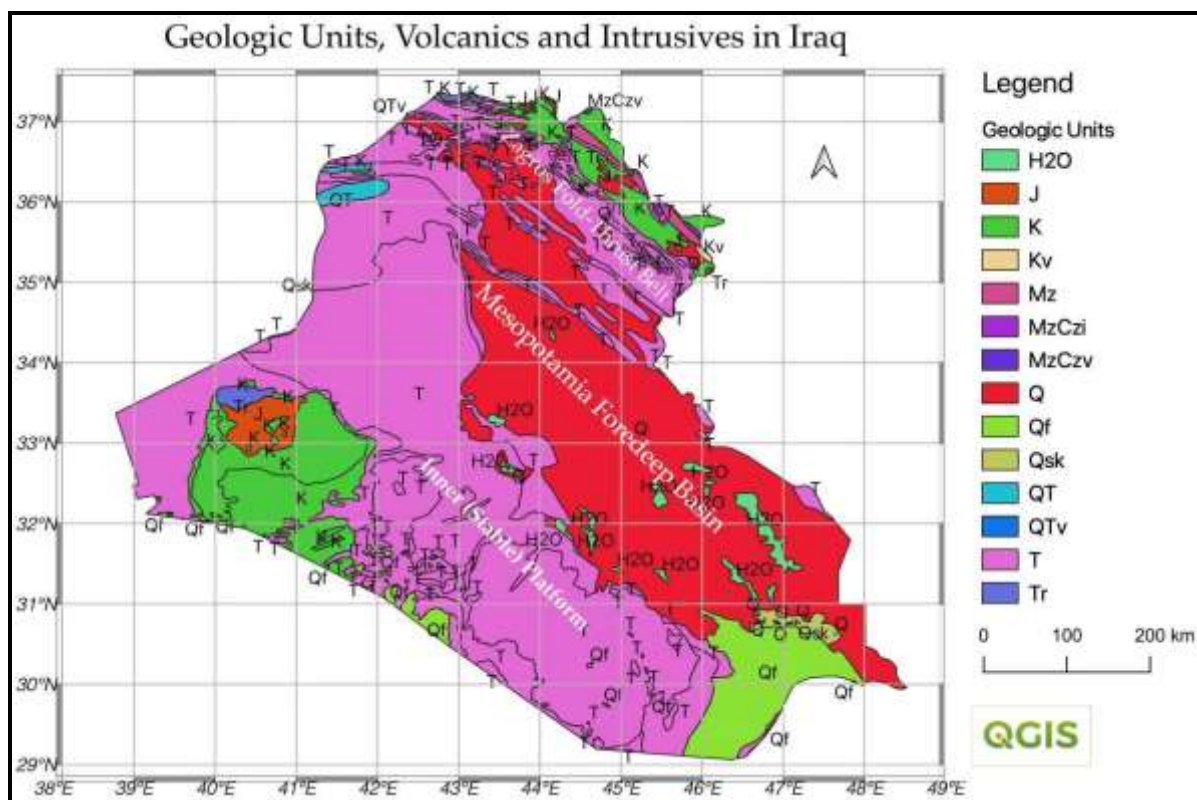


Fig.3: Geologic units, volcanics and intrusives of Iraq. Mapping: QGIS

## PREVIOUS WORK

From an analysis of previous research and literatures, the following key issues stand out in relation to the geology of Mesopotamia Foredeep Basin:

- i. The Mesopotamian Foredeep Basin in southern Iraq holds over 30% of the found Iraqi oil reserves in the Mishrif Formation (Aqrawi *et al.*, 2010; Mahdi *et al.*, 2013);
- ii. The Mishrif Formation is one of the principal carbonate reservoirs in Central and Southern Iraq. Its accommodation was defined by the regional tectonism and geologic evolution controlling the deposition conditions (Aqrawi *et al.*, 1998, 2010; Aqrawi and Badics, 2015);
- iii. The Mishrif Formation has predominant mineral components of calcite and dolomite and includes mudstone, wackestone, packstone, grainstone, floatstone, and rudstone with 15 principal sedimentary microfacies, formed during the two regressive cycles: 1) basin; 2) reef-shoal, to lagoonal environment (Al-Dabbas *et al.*, 2010).
- iv. The southern Mesopotamian Foredeep Basin demonstrates variations in the types of oils based on maturity. The oils are sourced from the marine carbonate-rich rocks (Type II-S kerogen), mostly from algal and microorganisms (Al-Khafaji *et al.*, 2021);
- v. The northern Mesopotamia Foredeep Basin shows different depositional environments and geochemical content (vanadium and nickel) in crude oils, which points at varying nature of deposits: marine, land and lacustrine (Abdul *et al.*, 2018);
- vi. The notable oil and gas condensate reservoir in western Iraq is the Akkas Formation discovered in sandstone reservoirs of Early Silurian and Late Ordovician age. The Lower Silurian sandstones of the Akkas Formation are characterized by a mean porosity of 6.5% and permeability of 0.2 mD (Aqrawi *et al.*, 2020);
- vii. The outstanding uranium anomaly in the region of the Basrah Governorate covering ca. 20,000 Km<sup>2</sup> and several other anomalies in the Desert Terrain. The main anomalous zones in the soils of the Desert Terrain are related to the Paleocene phosphorite exposures in the Akashat and Nukhaib regions (Al-Bassam and Yousif, 2014; Al-Bassam, 2021).
- viii. Structural geologic evolution of the Mesopotamia Foredeep is well reflected in the deposits of sands and silts below the surface alluvium of the Mesopotamian Plains near Basrah, Iraq that yielded a marine molluscan fauna of Holocene age. These have also been discovered at the shallow depths in Amarah and Qurmat Ali, as reflected in numerous foraminifera from these deposits (Macfadyen and Vita-Finzi, 1978).
- ix. Regional geophysical and magnetic surveys showed that the Ahwar area of southern Mesopotamia, including the Umm Al-Binni Lake, was subjected to the differential tectonic subsidence of the basement faulted blocks, as the distribution of the lakes is controlled by such basement tectonic zones of weakness (Sissakian and Al-Bahadily, 2018).
- x. The geomorphological features of the Mesopotamian Plain include fluvial, lacustrine, and the Aeolian landforms with the fluvial units being the abundant and occasionally presented estuarine and marine forms in the SE regions of the plain. The terrain presents almost flat and vast lowland, with clear physiographic boundaries covered by Quaternary sediments with dominating fluvial origin and more flood plain sediments (Sissakian *et al.*, 2021).
- xi. The landscapes in the NW part of the Kurdistan Region of Iraq express the tectonic activity caused by Arabia-Eurasia convergence and Neogene climate change (Forti *et al.*, 2021).

The summarized key issues highlight the importance of the study area in geoscience exploration and the significance for cartographic visualization. The use of GIS visualization for integration of geologic and tectonic data and maps production has actively been reported and presented in various publications in geosciences (Gauger *et al.*, 2007; Frehner *et al.*, 2012; Lemenkova, 2020b, 2020c; Alipour *et al.*, 2020). This study was based on the following spatial datasets, including both raster and vector data:

1. Topographic map based on raster grid of the General Bathymetric Chart of the Oceans, abbreviated as GEBCO (GEBCO Compilation Group, 2020);
2. Geospatial Data Abstraction software Library (GDAL) for raster geodata formatting and information retrieval (GDAL/OGR, 2021);
3. Geologic data from the USGS: vector layers in ArcGIS format (.shp) on geology, oil and gas fields and geologic provinces of the Arabian Peninsula (Pollastro *et al.*, 1999);
4. 3D relief mapping using the raster ETOPO1/ETOPO5 (Amante and Eakins, 2009);
5. Geoid EGM-2008 raster grid in 2,5 arc-minute resolution (Pavlis *et al.*, 2012);
6. Satellite-derived gravity raster grid (Sandwell and Smith, 1997; Sandwell *et al.*, 2014);
7. DEM raster grid from R package ‘raster’ (Hijmans and van Etten, 2012);

## **METHODOLOGY**

### **■ Data**

The question of data integration and representation is crucial in geomorphological mapping of Iraq, since the relief of the Zagros mountains (Low-Folded and High-Folded Zones), sedimentary Widyan Basin-Interior Platform, Rutbah-Ga'ara Uplift, Jabal Hemrin, Jabal Sinjar, the Mesopotamia Foredeep Basin and other geomorphic structures reflect a variety of processes of the Earth's lithosphere. This includes the geodynamics of the Arabian and Eurasian tectonic plates, their geologic structure and lithological facies, distribution of the trends in geophysical anomaly fields, to mention a few. Still, the nature of geomorphology in Iraq is rather complex. Therefore, high-resolution data visualization may bring new light on the correlation between these processes. Hence, the first step in the methodology of this research was to combine several high-resolution datasets from the available open sources.

### **■ Tools**

The technical tools used in this work include the following: Generic Mapping Tools (Wessel *et al.*, 2019), QGIS (QGIS.org, 2021) and R programming language (R Core Team, 2020) using RStudio environment (RStudio Team, 2017). Specifically, two main libraries have been used: ‘tmap’ (Tennekes, 2012) and ‘raster’ (Hijmans and van Etten, 2012). Addition packages (depending on the ‘raster’) include the following packages: ‘sp’, which provides classes and methods for spatial data utility functions, ‘ncdf4’ for data processing in netCDF format, ‘RColorBrewer’ for color visualization and flexible color palette adjusting, and ‘sf’, which supports simple features for R language.

### **■ Algorithms**

The technical tools of cartographic data visualization raise the following questions:

- representation of the multi-source data (GEBCO, EGM-2008, etc) and their integration through the GIS projects using available examples (Lemenkova, 2020d);
- 2D and 3D data modelling (Lemenkov and Lemenkova, 2021);
- the introduction of a qualitative and quantitative modelling of R programming language, connected to geospatial DEM datasets;

- the use of mixed-tools approaches (scripting GMT, QGIS, R environment, GDAL) by plotting using available techniques (Lemenkova, 2020e) to process heterogeneous data (geology, geophysics, DEM geomorphology, topography) from the open sources;
- combination of raster and vector layers to illustrate categorical data of geology, and continuous fields of geophysical and topographic data;
- the need for deeper methods of data analysis which include machine learning and automatization through the scripting console-based mapping;
- the need of multi-format big datasets for integrated GIS visualization.

## RESULTS

The framework of this project was structured through the three different tools – GMT, QGIS and R – used for modelling and cartographic visualizing of data by different methods.

The approaches in geologic data visualization are diverse: traditional GIS with existing methodology available in previous studies (Al-Zubaydi *et al.*, 2016; Suetova *et al.*, 2005a, 2005b; Lemenkova, 2020f; Klaučo *et al.*, 2013a, and 2017), stratigraphic columns traditional in geological mapping (see e.g. de Vera *et al.*, 2009; Edilbi, 2020), calculating landscape metrics (Klaučo *et al.*, 2013b, 2014), assessment of petroleum prospects (Sadooni, 2007).

Other techniques include geological cross-section techniques for data visualization (Le Garzic *et al.*, 2019), applied programming (Lemenkova, 2019b, and 2019c), 2D and 3D plotting (e.g. Aziz *et al.*, 2015, and 2019; Lemenkova, 2019a, 2020g; Abed *et al.*, 2020), automated cartographic data vectorization (Schenke and Lemenkova, 2008), scripting cartographic techniques (Lemenkova, 2019d). These approaches enable effective visual assessment of the properties of the studied geologic structures. The SRTM based DEM is widely used in geomorphological investigations (Burtscher *et al.*, 2012; Lemenkova, 2021) for computing curvature, modelling, classifying the folded surface into shapes, visualizing relief, since surface topography reflects the geologic fold shapes. This study also used DEM in R dataset used for modelling slope and aspect of the Iraqi relief (Fig.7 and Fig.8).

The results include 7 new maps created by the integrated data analysis and various softwares. The analysis of the outcomes shows the following results.

Fig.1 shows topographic map of Iraq. Quantitative data used in this map are gathered from GEBCO and processed by GMT. These shown the general map of Iraq processed by the combination of the GMT modules: ‘grdimage’ for mapping the grid, ‘psscale’ for plotting legend, ‘grdcontour’ for adding isolines (every 500 m), ‘psbasemap’ for mapping grid, title and cartographic elements on the map. The analysis of the relief range by GDAL shows the variations in the topography Minimum = -69 m in the Arabian Gulf, Maximum = 3754 m asl in the NE of the country.

Fig.2 shows the geologic provinces of Iraq that include the following: Anah Graben, Euphrates/ Mardin, Hail-Ga'ara Arch, Khleisha Uplift, Mesopotamia Foredeep Basin, Rutbah Uplift, Wadi Surhan Basin, Widyan Basin–Interior Platform, Zagros Fold Belt. The map has been visualized in the QGIS.

Fig.3 shows the geologic units of Iraq. The dominating types are Quaternary (Q) and Tertiary (T) that roughly divide the country into two segments, the south-western and the north-eastern. The other formations include Cretaceous (K), Mesozoic Cenozoic intrusives (MzCzi), Mesozoic Cenozoic volcanoes (MzCzv), Cretaceous volcanics (Kv), Triassic (Tr). The southern region is dominated by Quaternary fluvial sediments (Qf).

Fig.4 shows the 3D visualization of the Iraqi relief made using GMT with azimuth rotation 165°/30°. The 3D mapping shows the structural variation of the relief and is used for interpretation through different layers: contour vector data of topographic isolines and river network and mesh grid effectively demonstrating the location of Zagros contrasting with the Mesopotamia Foredeep Basin. The overlay of 2D layer over the 3D grid exemplifies the conceptualized spatial data integration through the connected datasets (ETOPO5 and fluvial network with main rivers of Tigris and Euphrates) with different values using the GMT modular scripting system.

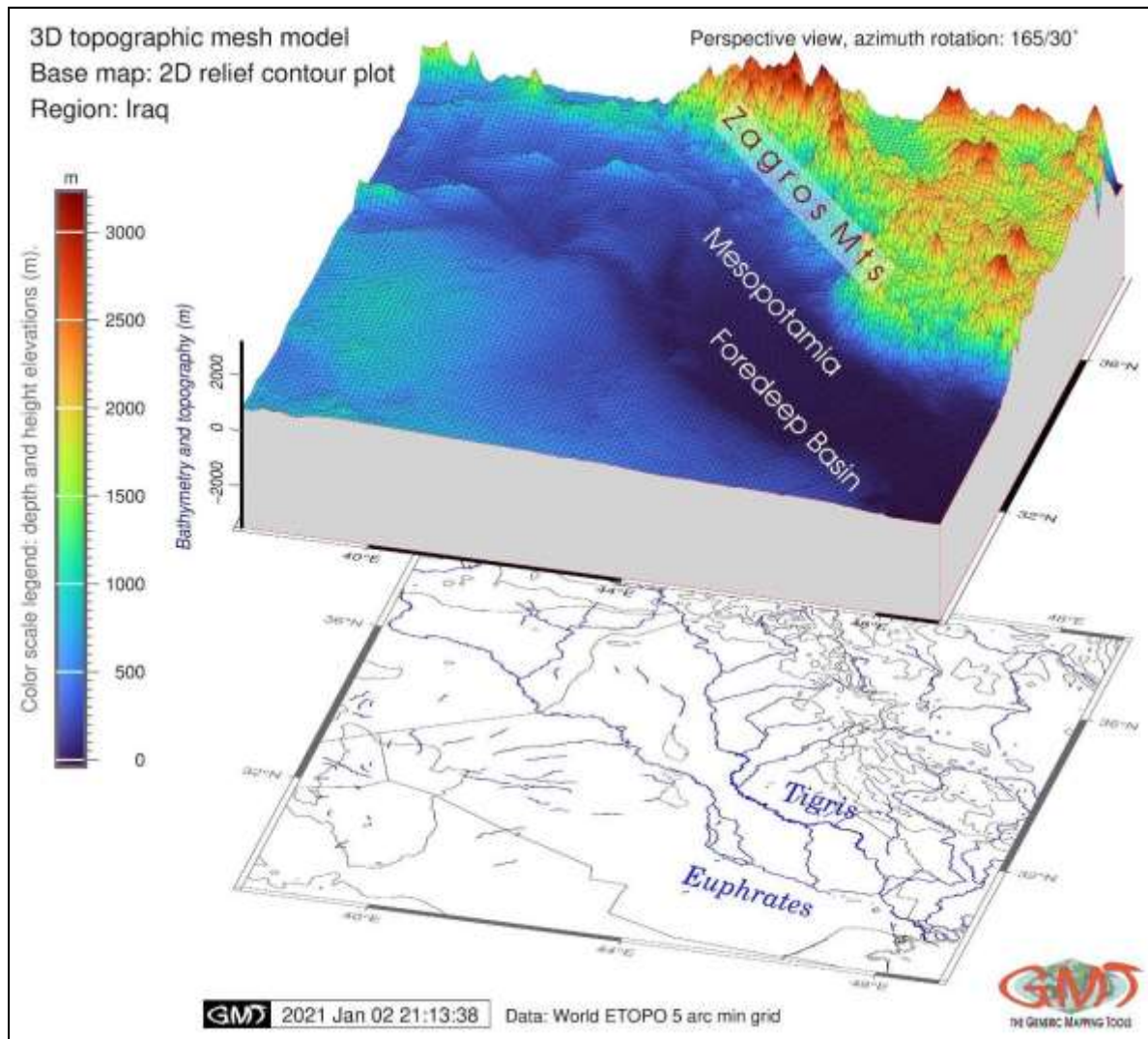


Fig.4: 3D model of the Mesopotamia Foredeep Basin. Mapping: GMT

Fig.5 shows the geoid undulations over the study area with clearly visible trend of the increase in data values in north-west direction. That is, the lowest, negative values of geoid (-17 m) are notable over the Arabian Gulf which reflects the continuum of the Indian geopotential minimum. The EGM-2008 derived geoid undulation values were visualized and compared with the recent works (Abdulrahman, 2020).

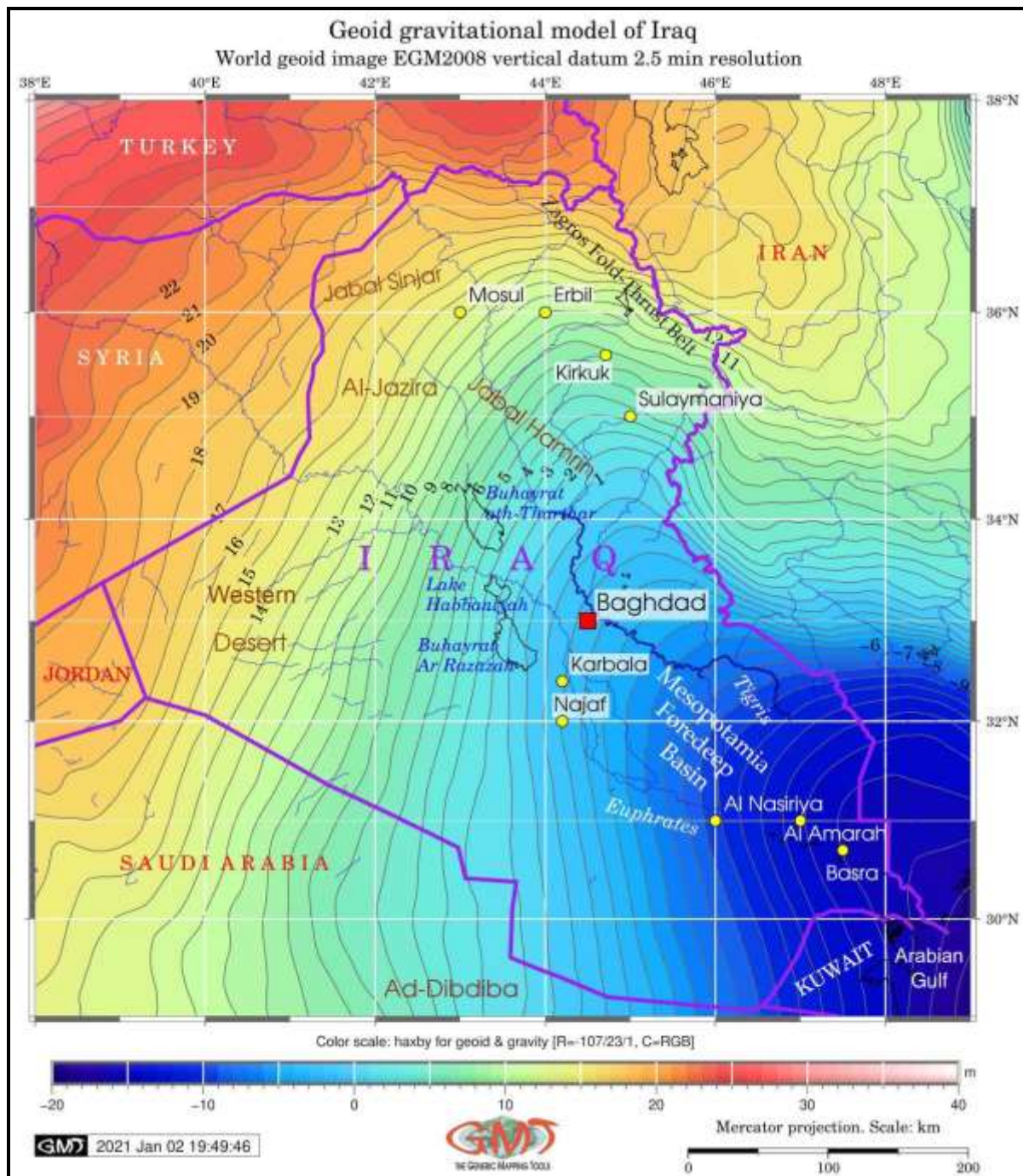


Fig.5: Geoid model of Iraq. Mapping: GMT

Fig.6 shows the gravity anomalies by the geophysical grids over the region of Iraq. Supporting the existing findings (Al-Farhan *et al.*, 2019; Mousa *et al.*, 2020), this study contributes to the visualizing and modeling of the geophysical fields in Iraq by visualizing the raster grid over the whole country using GMT.

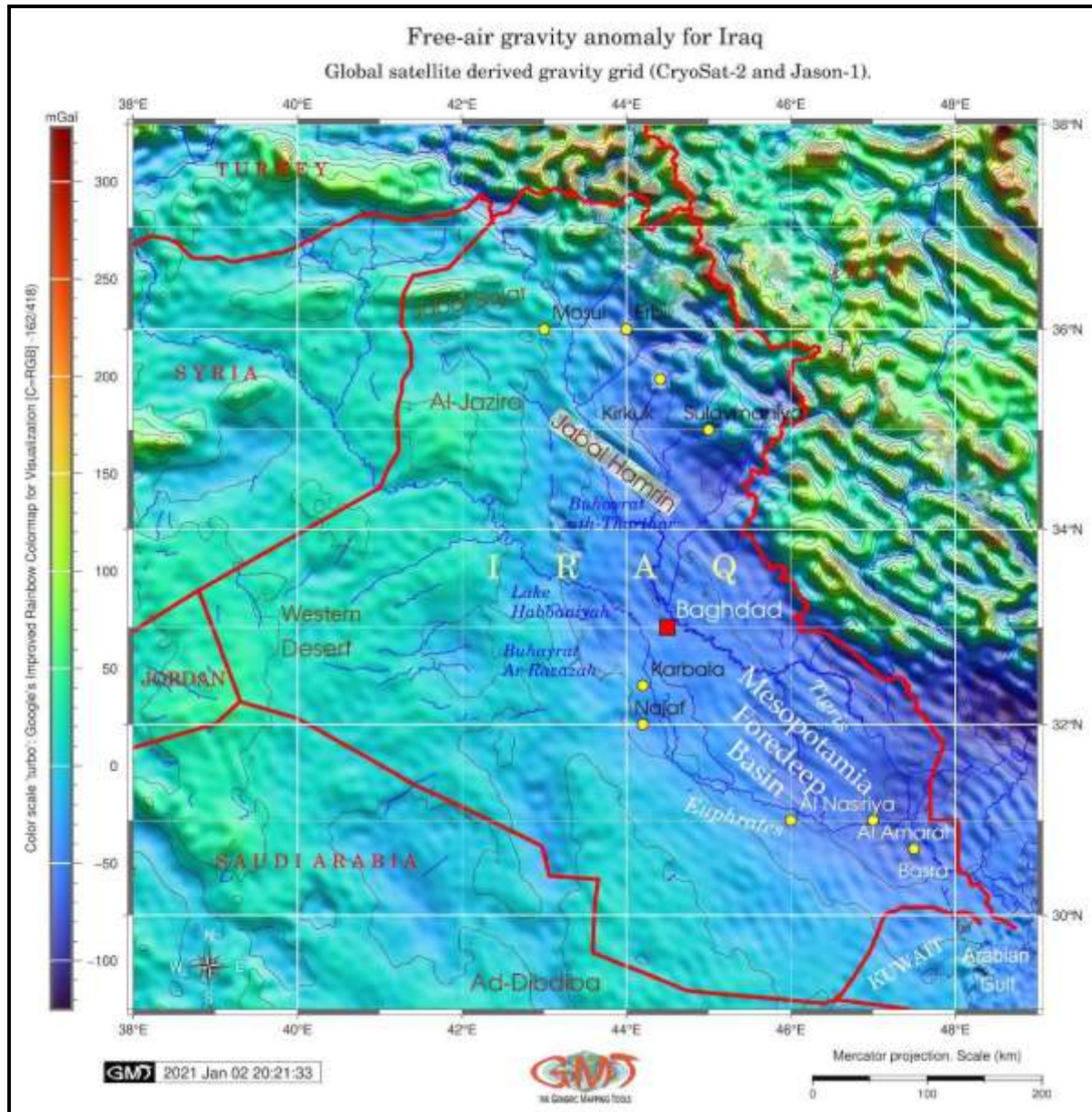


Fig.6: Free-air gravity anomaly fields in Iraq. Mapping: GMT

Fig.7 shows the aspect orientation of the relief (West-East-South-North) and derivatives by R. The R connected to the embedded dataset which includes the DEM for processing slope, aspect and hill shade of the relief of Iraq. The data processing was performed using both theoretical algorithms of the geomorphometric computation of topographic relief using ‘raster’ package of R, and conceptual cartographic visualization using ‘tmap’ package of R. The data were visualized by ‘Spectral’ color palette using ‘RColorBrewer’ package.

Fig.8 shows the slope steepness of the relief using R where the north-eastern segment of the country demonstrates the highest slope steepness (colored as dark green) and the most gentle steepness is situated in the fluvial valleys of Tigris and Euphrates (yellow color) with intermediate variations in the other regions. The data were visualized by ‘Viridis’ color palette using ‘RColorBrewer’ package.

The comparability of the datasets was achieved through the adjusted coordinate extend in GMT and clipped region of the whole country in R package 'raster' and QGIS where the clipping has been achieved using 'Processing Toolbox' by 'Vector Overlay' function using 'Clip' operation for selecting the geological vector layer only for the country level covering Iraq. In turn, the mask for the country was made previously using the polygon of the country by the 'Vector Selection' function using 'Extract by attribute' function that enabled to pick up the country polygon from the world vector layers of the country's borders.

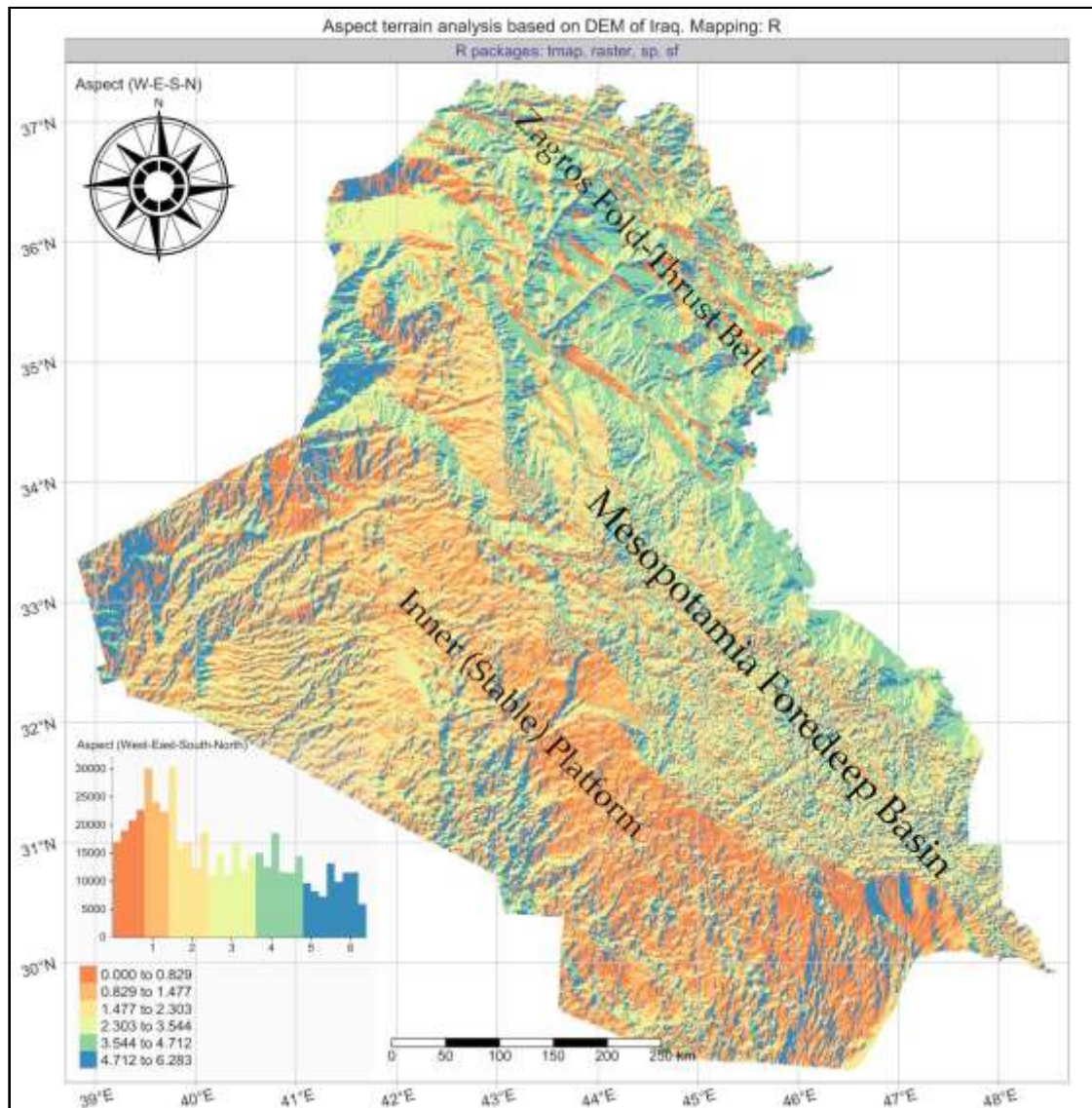


Fig.7: Aspect orientation on geomorphological map of Iraq. Mapping: R

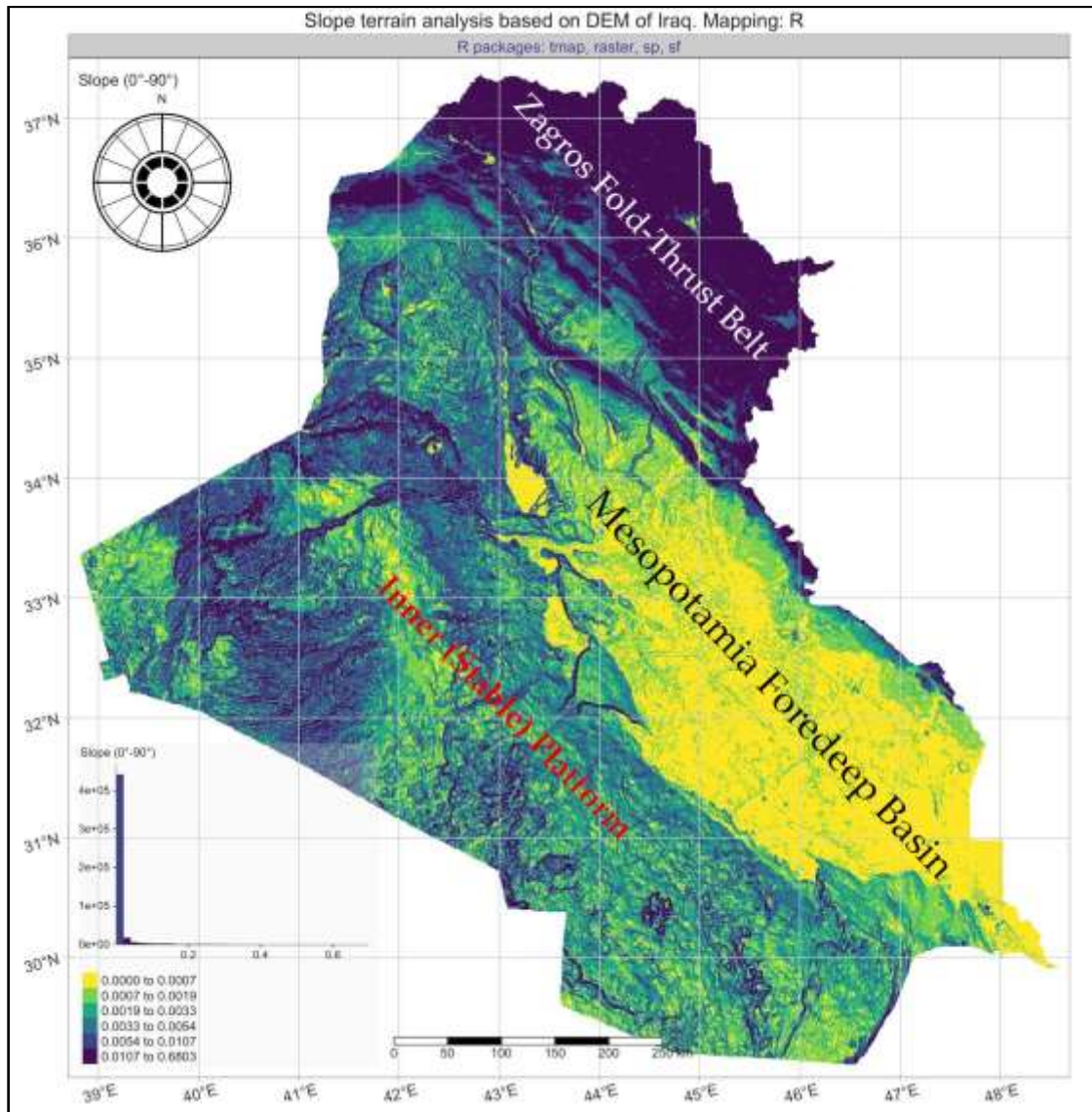


Fig.8: Slope terrain on geomorphological map of Iraq. Mapping: R

## DISCUSSION

The present study has demonstrated integrated data collection using datasets of different grades of complexity and varied spatial resolution (e.g. 2.5 arc-minute of EGM-2008, 15 arc-second of GEBCO grid etc), processed by GMT, QGIS and R tools for geomorphologic, geologic and topographic interpretation of the visualized maps. The semantic interoperability between various layers and datasets was addressed by using different approaches in mapping and 2D and 3D modelling using scripting approach in GMT, programming in RStudio using R syntax and traditional mapping in QGIS. By doing so, the layers were processed by multiple representations of the qualitative geologic entities, quantitative geophysical fields and continuous topographic structures of Iraq, using different ways of categorizing and visualizing multi-source data.

The scale of the GMT maps (1: 7,000,000) was influenced by the best representation of the datasets (GEBCO, EGM-2008, gravity grid) at the appropriate resolution covering the whole country, while the QGIS based maps (in Fig.2 and 3) have smaller cartographic scale

(1: 10,000,000) due to the included enlarged legends that are constrained by the extended legends including geologic provinces and units. The analysis of the presented new 8 maps contributes to the additional knowledge on geology, geomorphology and geophysics in Iraq. The findings add new visual information to the pool of publications on the geology and geomorphology of Iraq.

Combining the available geological and geophysical information, the paper presents a series of new 8 maps created by means of integrated cartographic approach of GMT, QGIS and R language (RStudio) showing the geomorphological, geological, topographic and geophysical setting of Iraq and visualizing, among others, Zagros Fold and Thrust Belt, Mesopotamia Foredeep Basin; extending in general NW – SE directions, geologic provinces and units of the study area well correlating with topographic isolines, geophysical anomaly fields and geoid undulations. The demonstrated geologic complexity of the Iraqi region mirrored the tectonic movements of the Arabian and Eurasian plates collision, and in turn, resulted in varied geomorphology, heterogeneous slope and aspect patterns, thrust orientation, Zagros Mountains orogenesis, faulting and folding in the sedimentary cover and finally formation of the oil plays.

## CONCLUSIONS

Processing multi-source datasets using various tools (GMT, R, QGIS) rises challenging questions of the cartographic aspects. Identifying the most suitable geographic resolution, projection and scale for plotting of data was adjusted to the country of Iraq and for the selected area of the Mesopotamia Foredeep Basin or Zagros. In this study, the projection was selected as Mercator, because it suits the visualization goal, well represents the country without distortions at the given latitudes and longitudes (the exact selected area coordinates is 38° – 49° E, 29° – 38° N).

As explained in the literature review (Ma'ala, 2009; Yacoub, 2011a; Mustafa, 2011; Fouad and Sissakian, 2011), the geology and geomorphology of Iraq mirror the tectonic processes of the Arabian and Eurasian plates movements (Jawad Ali and Al-Ani, 1983; Sissakian *et al.*, 2020b; Elias *et al.*, 2020). Therefore, the Mesopotamia Basin presents a rather complex stratigraphic structure, being an integral part of the Zagros Fold – Thrust Belt, developed as a result of the last phase of Alpine Orogeny during Pliocene to Early Pleistocene (Yacoub, 2011b; Abdalnaby, 2019; Elias *et al.*, 2019). Comprehensive cartographic methods for an integrated mapping, visualization, modelling and analysis of such a complex object as geomorphology of Iraq beyond multiple approaches for the traditional GIS are still lacking. The existing publications and reports have, not been sufficiently comprehensive in terms of 2D and 3D visualization of the geomorphology of the Mesopotamia Foredeep Basin and Zagros Fold and Thrust Belt, and presented new maps contributed to such a demand.

Integrated cartographic method in studies of Iraq geomorphology, geophysics and geology may have other applications besides visualization: complementarity with existing geological datasets (including stratigraphic columns and statistical plots), contribution to the development and prognosis of new oil plays due to the overlay of geophysical, topographic and geological data, detailing and expansion of the existing cartographic database on visual information of the Mesopotamia Basin. New cartographic layouts also lead to an enriched comprehension or added knowledge on the relief structure of the Zagros due to the detailed visualization of the aspect orientation and slope steepness of the mountains resulting from the R based modeling in libraries 'raster' and 'tmap' processing DEM by the embedded algorithms.

## ACKNOWLEDGEMENTS

The author cordially acknowledges Drs. Ahmed Saker, Khaldoun Al-Bassam and two anonymous reviewers for their constructive comments, careful corrections and remarks. The author is particularly grateful to the Executive Editor Dr. Hussein A. Jassas from Iraqi Geological Survey, Baghdad, whose help with Arabic language improved the Abstract. The author sincerely thanks the Technical Editor Mr. Hayder Hafud for the editorial formatting of the manuscript. This research has been implemented into the framework of the project No. 0144-2019-0011, Schmidt Institute of Physics of the Earth, Russian Academy of Sciences.

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