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Research Article

Hakim Saibi*, Diab Bakri Hag, Mohammed Saeed Mohammed Alamri, and Hamdan Abdo Ali

Subsurface structure investigation of the United Arab Emirates using gravity data

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Abstract: The crustal structure beneath the United Arab Emirates (UAE) is still relatively unknown. Here, we use regional gravity data to constrain the subsurface density distribution and structure of the crust of the UAE by applying diverse gravity derivatives methods such as horizontal derivative (HDR), analytic signal (AS), and tilt angle (TA) to analyze the subsurface structure and perform three-dimensional (3D) gravity inversion for imaging crustal structure from the surface down to 35 km depth. The results are compared with known geological regional structures and the location of the petroleum fields.

The Bouguer anomalies range from –100.8 to 113.5 mGal. The 3D gravity inversion results and the maximum Bouguer values coincide with the ophiolitic Hajar mountains in the east and the successive anticlines (uplifted basement rocks) and synclines in different parts of UAE, which could be promising sites for future mining and petroleum exploration. Also, the 3D density model results and the minimum Bouguer anomalies are located over the Aruma Basin, eastern UAE Platform, and Low Central UAE Platform, which can be the places for deep groundwater aquifers. These new results from HDR, AS, and TA successfully identify known geological structures, especially in the eastern part of UAE.

Keywords: gravity, horizontal derivative, analytic signal, tilt angle, structure, inversion, UAE

Diab Bakri Hag, Mohammed Saeed Mohammed Alamri, Hamdan Abdo Ali: Geology Department, College of Science, United Arab Emirates University, Al-Ain, United Arab Emirates

1 Introduction

The gravity method is a popular geophysical technique used in oil and gas exploration and in a number of geological resource exploration fields. In oil exploration, the gravity method is particularly applicable in salt provinces, overthrust and foothills belts, underexplored basins, and targets of interest that underlie high-velocity zones. The gravity method is frequently used in mining to map subsurface geology and to calculate reserves for some massive sulfide-ore bodies. In addition, there has been a modest increase in the use of gravity techniques in specialized investigations for shallow targets, applicable in archeology, hydrogeology, and geothermal studies [1,2].

Recent spatial technology developments have facilitated the study of Earth by recording valuable geophysical data such as gravity measurements using the Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP) [3], Gravity Recovery and Climate Experiment (GRACE) satellites [4], and Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite [5]. CHAMP mission (2000–2010) objectives included the observation of the Earth's gravity and magnetic fields and atmospheric research equipped with a GPS and an accelerometer. GRACE was launched in 2002 with a mission to measure and monitor large-scale gravity field variations with time for the purpose of studying changes in continental water storage and the extent of ice sheets [6].

These datasets have worldwide coverage and are open access. They provide a new opportunity to estimate the crustal thickness (low-density crust over high-density mantle). Today, there are multiple gravity data sources (satellite, airborne, ground, and seaborne) available for integration to create more accurate, large-scale crustal thickness models.

In addition to gravity satellites, gravimeters measure the Earth's gravitational field and can be used in sea, ground, and air settings. Gravity data help in developing crust and lithosphere models at different scales, which show the density distributions in the upper crustal layer. These results improve the understanding of basins that

^{*} Corresponding author: Hakim Saibi, Geology Department, College of Science, United Arab Emirates University, Al-Ain, United Arab Emirates, e-mail: saibi.hakim@gmail.com, hakim.saibi@uaeu.ac. ae, tel: +971-0543701526

may preserve natural resources (oil, gas, and water) and detect major tectonic/structural features.

Seismic data are often used to study crustal structure; however, gravity data can provide additional data support and improve spatial resolution, especially when seismic profiles are not available or too costly. Gravity and seismic data can also be combined for a better understanding of crustal structure. Ref. [7] showed how gravity data from multiple sources and collection settings are integrated with 2D seismic profiles to produce a 3D density model of the crust of Greece. Ref. [8] applied joint modeling of gravimetry, topography, and geoid data to create a new model of the lithospheric structure of the Tibetan Plateau and its surroundings. Ref. [9] integrated seismic and gravity data to investigate the deep structure of the Western South African passive margin.

There are many applications of gravimetry for studying crustal structure in different parts of the world, especially after the launch of the GRACE satellite in 2002. For example, ref. [10] investigated the European lithosphere from satellite gravity data (CHAMP and GRACE) and terrestrial data. Ref. [11] used gravity to determine the depth of the Moho in Australia. Ref. [12] determined the thickness of crust and its structure in the Gabon Margin using seismic reflection and gravity data. Ref. [13] applied power spectral analysis to gravity data sets obtained from EGM (Earth Gravitational Model, 2008) to study the crustal structure beneath Cameroon. Ref. [14] successfully determined the crustal and lithospheric structures in the southeastern Mediterranean and northeastern Egypt using gravity data. Ref. [15] clarified the lithospheric structure in the North China Craton using GOCE satellite gravity gradient data. Ref. [16] studied the crustal architecture beneath the Levant basin using global gravity model data. Ref. [17] developed 2D/3D density models from gravity data on the large scale to better understand the occurrences of earthquakes and aid in the detection of possible seismic hazard zones.

There are few studies of the basement rock morphology and regional structures of the United Arab Emirates (UAE) and no complete crustal density model. Recent studies have focused on only small areas of the UAE. For example, ref. [18] focused on the basement structure offshore from Abu Dhabi in the Arabian Gulf, and ref. [19] studied the ophiolite deep structure beneath the UAE using potential field and seismic data.

This study investigates the crustal thickness and structure of the UAE based on available satellite gravity data. The inverted gravity data are used to produce density models that will help detect major subsurface structural configurations and estimate the depths of major sedimentary basins.

The objectives of this study are as follows: (1) creating a new Bouguer anomaly map of the UAE from satellite gravimetric data, (2) developing new density models beneath the UAE from the surface to the deeper part of the crust, and (3) understanding the relationship between gravity and known geological structures, location of main petroleum fields, interpreted geological contacts, and known sedimentary basins. This study provides important support for oil exploration companies in finding new reservoirs.

2 Geology and tectonic settings

The UAE is located on the Arabian Plate that is moving northward in collision with the Eurasian Plate at 22 mm/ year [20]. The UAE crust is part of the eastern basement of the Arabian crust. The basement of the Arabian Platform (eastern basement) is stable, having experienced no major tectonic activity since 750 Ma [21]. Since that time, the Eastern basement was subjected to continuous gentle subsidence and sedimentation during the Neoproterozoic to Phanerozoic. The thickness of the crust is around 40-45 km [20] beneath the Arabian Platform. The western part of the UAE is covered by Cambrian salt basins as part of the Southern Gulf. The eastern part of the UAE belongs to the UAE-Oman Ophiolite domain. This ophiolitic domain represents a fragment of ocean crust that was obducted onto the continental margin.

The UAE is located on the southern side of the Arabian Gulf, at the northeastern edge of the Arabian Plate (Figure 1). Although large areas of the country are covered in Quaternary sediments, the bedrock geology is well exposed in the Hajar mountains and the Musandam Peninsula of the eastern UAE (Figure 2) and along the southern side of the Arabian Gulf west of Abu Dhabi.

The geology of the UAE includes thick Paleozoic, Mesozoic, and Cenozoic marine and continental sedimentary rocks overlying deeply buried Precambrian rock. The region has extensive oil and gas resources and was deformed during the last several million years by distant tectonic events [20]. The UAE basement structure is still relatively unknown except for a few local study sites [22].

3 Methodology

In this study, the gravity method is used for mapping of the basement morphology, to delineate subsurface

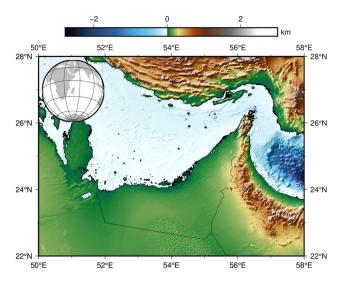


Figure 1: Location and topography map of UAE.

structures across the UAE, and to detect the major basins and geological structures. To achieve this goal, we have used available satellite data, which was acquired across the entire UAE.

3.1 Datasets and Bouguer anomaly

Gravity data were downloaded from Geosoft Seeker Tool covering the UAE [23]. The Bouguer gravity field was then gridded to create a Bouguer anomaly map. Different gravity derivative methods (horizontal derivative, analytic

signal, and tilt angle) were applied to delineate the subsurface structures. Next, a 3D gravity inversion was applied to the Bouguer anomaly data using Geosoft software to image the density variations and subsurface structural features in the UAE. The gravity data are open to the public, with the source of the data found at the Center for Space Research, the University of Texas at Austin (http://www.csr.utexas.edu/grace/gravity). The gravity dataset was created by NASA (The National Aeronautics and Space Administration) on October 29, 2004, under the project name: Gravity Recovery and Climate Experiment, Details on gravity data and applied corrections are discussed in ref. [24]. The Gravity method is a passive geophysical method, which measures the Earth's gravity field. The subsurface density distribution can be estimated through forward and inverse modeling [25]. Knowledge of the subsurface density distribution has many applications in earth sciences such as detecting faults, studying the morphology of basement rocks, subsurface geological features, and locating high-density bodies (minerals) underground. The Earth's gravity field can be measured at ground level, sea level, and from airborne equipment. Terrain corrections are first applied to all such measurements. After corrections of the raw value, the Bouguer anomaly (BA) is obtained. The Bouguer anomaly is the most widely used gravity database to understand the subsurface mass variations. The complete Bouguer gravity anomaly (CBA) at a specific station is calculated using this equation:

$$CBA = G_{abs} - \gamma + F - 2\pi G \rho H + T_c \rho \qquad (1)$$

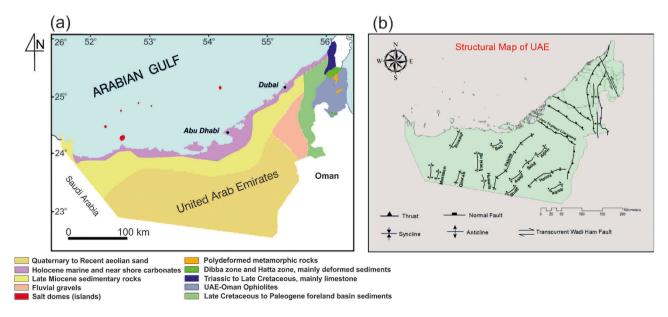


Figure 2: (a) Geological map of UAE and (b) structural map of UAE.

where G_{abs} is the absolute gravity, y is the normal gravity, F is a free-air correction, $2\pi G\rho H$ is Bouguer correction, and $T_c \rho$ is the terrain correction. H is the elevation and ρ is the density. More details on gravity corrections can be found in ref. [26].

In general, when the Bouguer gravity is high (not necessarily positive), it means that a high-density body lies beneath the surface. This may be interpreted as an uplifted basement beneath the region or intrusion of high-density rocks (basaltic dykes, for example). If the Bouguer anomaly is low (not necessarily negative), this may be explained by basement rocks being deeper than the surrounding region and/or a thick sedimentary rock sequence in a region of high-density basement rocks or basement composed of low-density rocks. The BA values are relative and are interpreted in the context of the studied area, which means they should be compared with other BA values located nearby and surrounding the study area.

3.2 Applied methods

To interpret BA values, there are, in general, three types of methods: (1) forward modeling, (2) inversion, and (3) derivative methods, which amplify the noise in the datasets. The gravity derivative methods are computed from the first and second derivatives of the gravity field. The second derivative of the gravity field is not commonly used because it contains high noise. There are many first-derivative gravity field methods, working in horizontal (x, y), vertical (z), or in all directions (x, y, z)that have been developed in the previous decades. The most common methods are horizontal derivative (HDR), tilt angle (TA), and analytic signal (AS), all of which are applied in this study.

3.2.1 Tilt angle (TA)

The TA method was designed to enhance and sharpen the gravity anomalies. The advantage of TA is that the zero value of TA traces the boundaries of the gravity source bodies. The TA is calculated by the following formula [27]:

$$TA = \tan^{-1} \left\{ \frac{\partial g}{\partial z} / \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2} \right\}, \tag{2}$$

3.2.2 Horizontal derivative (HDR)

HDR method has been used extensively to locate the boundaries of density contrast from gravity data or pseudogravity data. The method contends that the horizontal gradient of the gravity anomaly caused by a tabular body tends to overlie the edges of the body if the edges are vertical and well separated from each other [28,29]. The greatest advantage of the HDR method is that it is least susceptible to noise in the data because it requires only the calculation of the two first-order horizontal derivatives of the field [30]. The HDR method is also robust in delineating both shallow and deep gravity sources, in comparison with the vertical gradient method, which is useful only in identifying shallower structures. The equation of HDR [29] is

HDR =
$$\sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2}$$
, (3)

where $(\partial g/\partial x)$ and $(\partial g/\partial y)$ are the horizontal derivatives of the gravity field in the x and y directions, respectively.

3.2.3 Analytic signal (AS)

The AS is another derivative method that uses the three components of the gravity data in the three directions $(x, \frac{1}{2})$ y, and z) as defined by ref. [31]:

$$|AS(x, y)| = \sqrt{\left(\frac{\partial g}{\partial x}\right)^2 + \left(\frac{\partial g}{\partial y}\right)^2 + \left(\frac{\partial g}{\partial z}\right)^2},$$
 (4)

3.2.4 Three-dimensional (3D) gravity inversion

Mapping the Earth's structure in two and three dimensions can be addressed through various inverse techniques. Many researchers prefer inverse methods to forward modeling methods because inversion produces quantitative solutions that can be assessed more readily than the iterative trial-and-error method of forwarding modeling.

Inversion is defined here as an automated numerical procedure used to construct a model of subsurface physical property (density contrast using gravity data as input) variations from measured data and any prior information independent of the measured data.

In this study, a three-dimensional (3D) gravity inversion is performed using the VOXI Earth Modelling tool (Geosoft Oasis Montaj Ver.8.5). Details on the inversion procedure can be found in ref. [32–35]. Further information about the gravity inversion method can be found in ref. [36,37]. 3D density models at different depths were developed from the 3D gravity inversion. The study area was discretized into cells, $50 \times 41 \times 7$ cells in the X, Y, and Z directions, respectively (Figure 3). The cell sizes are $10 \times 10 \times 5$ km in the X, Y, and Z directions, respectively.

4 Results and discussion

4.1 Bouguer anomaly map

The Bouguer anomaly map covering the UAE has values ranging from -100.8 to 113.5 mGal. High Bouguer values are mainly located in the eastern and southwestern parts of the UAE (Figure 4). The high Bouguer values in the eastern part of the map are explained by ophiolitic mountains (Hajar mountains) and are related to the allochthonous series of the Semail ophiolites and thrust sheets [38]. The high values in the southwestern part of the UAE correlate with anticlines whose cores could contain high-density rocks. The low Bouguer anomaly values may represent poorly explored basins. The low Bouguer anomalies are mainly observed in two onshore regions: (1) eastern UAE and (2) western UAE. In the eastern part of UAE, the NW-SE trend low Bouguer anomaly (blue region in Figure 4) shows the location of the known Aruma Basin trend, and in the western UAE, the low gravity values are correlated to salt dome regions of the Rub' Al Khali basin [38]. In general, the known geological faults and thrusts are located at boundaries between high and low Bouguer anomalies (Figure 4), especially in eastern and central parts of UAE.

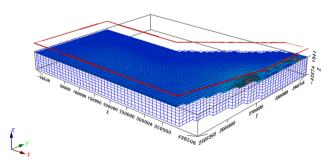


Figure 3: 3D mesh model of the study area. The topography is added to this mesh for the inversion purpose. Elevation values are from DEM data. The red line shows the boundary of the model. The X, Y, and Z values are in meters.

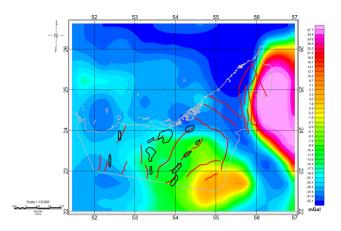


Figure 4: Bouguer anomaly map of the UAE. Faults, synclines and anticlines, and thrusts are indicated on this map as red lines. Oil fields are outlined in black. The border of the UAE (study area) is gray. Coordinates are in degrees.

The Bouguer anomaly map shows a very high value (>15 mGal) in the Eastern UAE and delineates the location of thrusts (Hagab and Semail) and very low Bouguer anomalies onshore and offshore of UAE. Such low Bouguer anomalies were interpreted as large diapirs of low-density Hormuz salt [39], and they are correlated with the location of salt domes and the existence of oil fields (Umm Shaif and Zakum). The low gravity in eastern UAE is associated with downward flexure of the Earth's lithosphere under the load resulting from the units thrust onto it from the east.

Ref. [38] used gravity data to constrain the Neoproterozoic basement structure in UAE from the derivative techniques (First Vertical Derivative, Total Horizontal Derivative, Tilt Derivative, and Euler Deconvolution) and Forward Modelling. Ref. [38] detected three distinct major structural regions: (i) fold, (ii) thrust belt, and (iii) foreland and salt provinces. These three major structural regions are observed in the Bouguer anomaly map of Figure 4.

4.2 Horizontal derivative (HDR)

The HDR map of the UAE shows values ranging from 3.8 to 216.1 mGal/m (Figure 5). The HDR of Bouguer gravity anomaly locations are changed horizontally, and the HDR changes are seen at geological structure borders, faults, or contacts and are characterized by maximum HDR values. The maxima of HDR values are mainly located in the eastern part of the UAE where ophiolitic mountains (Hajar mountains) are located and in the central parts of the UAE. The maxima in HDR represent the

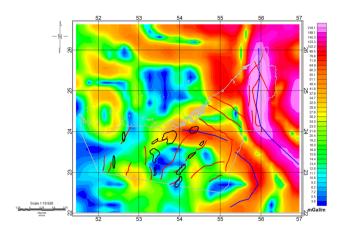


Figure 5: Horizonal derivative of gravity data of the UAE. Red lines represent faults and known geological structures. Blue line indicates the maxima value of HDR. Petroleum fields are outlined in black. The border of the UAE (study area) is the gray line. Coordinates are in degrees.

location of geological contacts and are represented by blue-colored lines in Figure 5. The interpreted contacts from HDR match known geological contacts (Figure 5).

4.3 Analytic signal (AS)

The AS map of the UAE (Figure 6) shows values ranging from 8.0 to 290.5 mGal/m. The high AS values are located in the northeastern part of the UAE and represent the location of mountains of dominantly ultramafic and metamorphic rocks with high-density values. We also find some isolated high AS signals in the central part of UAE (Abu Dhabi Emirate) that can be explained by the

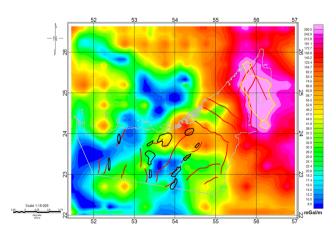


Figure 6: Analytic signal of gravity data of the UAE. Red lines represent faults and known geological structures. The yellow line contour shows the location of high AS values. Petroleum fields are black lines. The border of the UAE (study area) is gray. Coordinates are in degrees.

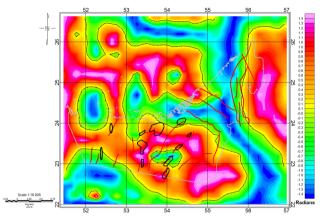


Figure 7: Tilt derivative of gravity data of the UAE. Black dashed line represents the zero value of TA. Red lines represent faults and known geological structures. Petroleum fields are outlined in black. The border of the UAE (study area) is gray. Coordinates are in degrees.

local uplift of the basement rocks. AS method is used mainly to detect high AS regions, which point to the existence of high-density bodies underground. The low AS regions are not analyzed in this study.

4.4 Tilt angle (TA)

The TA map of the UAE (Figure 7) shows values from -1.4 to 1.4 Radians. The zero values of TA are interpreted as

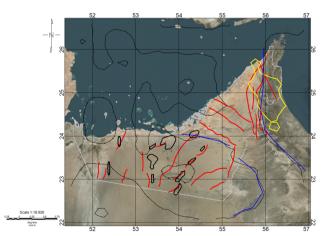


Figure 8: Interpretative map combining results from the HDR, AS, and TA of Bouguer anomaly of the UAE. Red lines show the geological structures, blue lines show the maxima of HDR, yellow contours show the maxima of AS, and dashed black lines show the zero value of TA. Black contours show the oil fields in Abu Dhabi Emirate. The border of the UAE (study area) is gray. Coordinates are in degrees. The basemap is satellite imagery from Google Earth of the study area.

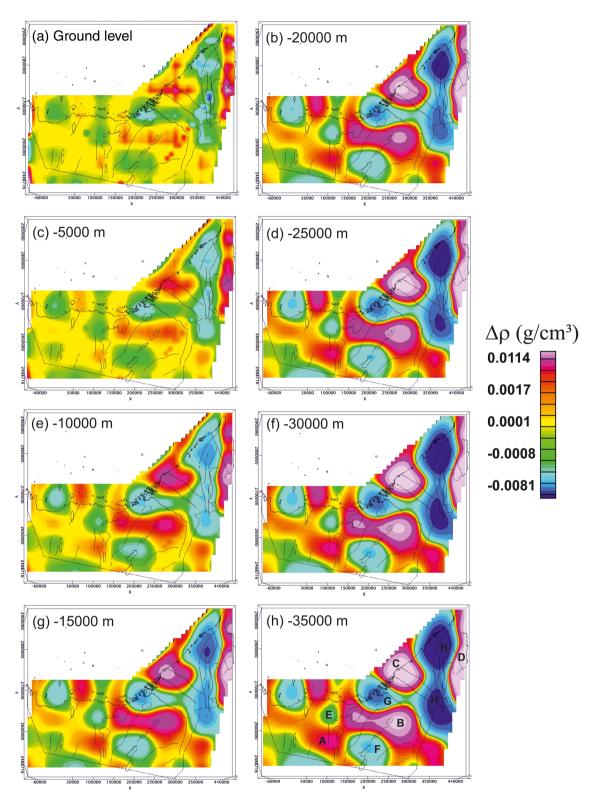


Figure 9: Results of 3D gravity inversions showing density contrast variations at different depths from ground level (a) to 35 km below surface (h). Different density signals are labeled A to H on the 35 km map, bottom right. A to D are high density regions, E to H are low density regions. The coordinates in easting and northing are in meters.

geological contacts (dashed black lines in Figure 7). The interpreted contacts are located in the eastern UAE and

align with geological thrust faults (the Hagab thrust). In some localities in the central and western parts of the

UAE, there are also matches with known geological features (syncline and anticline axes). We have to mention that TA involves derivatives in x, y, and z of Bouguer anomalies and this can amplify the noise.

Figure 8 presents the combination of the three gravity derivative results (HDR, TA, AS). The HDR results agree with the TA results in that the HDR delineates the eastern and western borders of the Eastern UAE Platform (Figure 8), which has Bouguer anomalies ranging from –40 to –20 mGal. The limits of AS border the UAE-Oman Ophiolite. On the other hand, in the Central UAE Platform, the three gravity derivative methods could not delineate the geological structures, represented by anticlines and synclines. This is likely to be due to these structures not being regional in scale compared with the regional structures in the eastern part of the UAE (thrusts). For this reason, they may be below the satellite data resolution.

The interpreted results from TA and HDR (Figure 8) showed a good correlation with the location of Semail and Hagab thrusts in eastern UAE, where the maxima of HDR values and the zero values of TA are located in the same location of known thrusting. Another interesting result from the TA and HDR methods in the Abu Dhabi region is a detection of a possible new Abu Dhabi Lineament (ADL) trending WNW-ESE (Figure 8) sub-parallel to the two knowns NW-SE ADL lineaments crossing Abu Dhabi city and related to the Najd fault system [38].

4.5 Gravity inversion

The results of the 3D Bouguer anomaly inversion are presented in Figure 9. The results are density contrast variations across the UAE from ground level to −35 km below the surface. The high-density regions are basement rocks (Proterozoic basement), which are uplifted in four main regions within the onshore portion of the UAE (A, B, C, and D, see Figure 9h). The very high density in the eastern part of the UAE and along the UAE-Oman boundary represents the location of the Semail Ophiolite. Such ophiolite rocks have high-density values (3,120 kg/m³ after ref. [19]). The low-density regions are thick sedimentary basins (>20 km), which are observed in four regions (E, F, G, H, see Figure 9h).

The results of 3D gravity inversion in the Eastern UAE Platform show correlations with existing synclines and anticlines where, in general, anticlines are located over high-density regions and synclines are located over low-density regions (Figure 9). Notable exceptions include Ghurab (west of the UAE) and Asab (Center of the UAE)

anticlines, which are located over low-density regions, and the Falaha syncline (Center of the UAE), which is located over a succession of low- and high-density regions.

If we compare the density models with existing oil fields, these oil fields are located in three different geological settings: (1) along the edges of uplifted basement rocks, (2) the top of uplifted basement rocks, and (3) within basins (Figure 9). The low-density anomaly located in the eastern part of the UAE trending N-S (the Ras Al Khaimah Basin, also called the Aruma Basin, region H in Figure 9h) contains very low-density contrast material and may extend to deeper parts of the crust. Such basins could contain water and oil resources. Many known geological structures and faults are in agreement with the 3D density models as they are located at the boundary between high-and low-density contrasts, especially for the eastern and central parts of the UAE.

The 3D gravity results revealed low- and high-density regions (Figure 9) that image the basement morphology changes in the UAE. The density models were obtained at different depths ranging from the ground surface to 35 km (b.s.l.). We can see some correlations with the 3D tomographic model results of ref. [40]: The low-density regions (G, H, F, and E in Figure 9) correspond to shear zone areas, and the high-density regions (B and C in Figure 9) correspond to the intra-oceanic arc. Furthermore, the trend and locations of high- and low-density anomalous zones have the same trend and location of changes as observed in the P-wave tomographic solution models [40]. Ref. [39] mentioned that the thickness of the sedimentary basin is around 10 km. In this study, we showed that the thickness of sedimentary rocks could reach more than 35 km.

5 Conclusions

A Bouguer anomaly map of the UAE is produced and shows values ranging from -100.8 to 113.5 mGal. High Bouguer values are located in the eastern part of the UAE where the Hajar ophiolitic mountains exist, and in the southwestern part of the UAE where anticlines are abundant.

The gravity derivative methods (HDR, AS, TA) applied to Bouguer anomaly data show an agreement with the Hagab thrust fault in the east of the UAE. Other contacts were detected as striking E-W and WNW-ESE. High values of AS coincide with the UAE-Oman Ophiolite. The high values of HDR coincide with the Jam Yaphour Lineament in the west and the eastern boundary of the Eastern UAE Platform.

The 3D gravity inversion results showed an elongated N-S low-density area in the eastern part of the UAE coinciding with the Aruma Basin and extending to the south of the UAE, which may host a deep groundwater aquifer system. The 3D density models show a succession of high- and low-density regions, especially in the central and western part of the UAE. These successions are correlated, in general, with known anticlines and synclines in the Eastern UAE Platform. The Bouguer anomaly maps also detected these alternating anticlines and synclines that may be of interest for future oil exploration. This work indicates that these regions have potential as petroleum reservoirs, located at the boundaries between high and low Bouguer anomalies, potentially indicating structural-stratigraphic entrapment systems.

The gravity satellite data cannot be used for regional geological studies, due to the lower resolution; however, it can be improved with the addition of ground gravity data to investigate local shallow and deep geological structures. The results of this study give an overview of the basement morphology and geological structures of UAE; however, a combination and confirmation from other geophysical studies such as seismic and electromagnetic methods are important to confirm the gravity models.

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References

- [1] Saibi H, Nishijima J, Ehara S. Processing and interpretation of gravity data for the Shimabara Peninsula area, south-western Japan. Mem Fac Eng Kyushu Univ. 2006;66(2):129–46.
- [2] Saibi H, Nishijima J, Hirano T, Fujimitsu Y, Ehara S. Relation between structure and low-temperature geothermal systems in Fukuoka city, southwestern Japan. Earth Planets Space. 2008;60(8):821–6.
- [3] GFZ. https://www.gfz-potsdam.de/en/section/geomagnetism/infrastructure/champ/. Accessed July, 2020.
- [4] NASA. https://www.nasa.gov/mission_pages/Grace/ index.html. Accessed July, 2020.
- [5] Dufréchou G, Martin R, Bonvalot S, Bruinsma S. Insight on the western Mediterranean crustal structure from GOCE satellite gravity data. J Geodyn. 2019;124:67–78. doi: 10.1016/ j.jog.2019.01.006.

- 6] Torge W. Geodesy. 3rd edn. New York: De Gruyter; 2001.
- [7] Makris J, Papoulia J, Yegorova T. A 3D density model of Greece constrained by gravity and seismic data. Geophys J Int. 2013;194(1):1–17. doi: 10.1093/gji/ggt059.
- [8] Jiménez-Munt I, Fernàndez M, Vergés J, Platt JP. Lithosphere structure underneath the Tibetan Plateau inferred from elevation, gravity and geoid anomalies. Earth Planet Sci Lett. 2008;267(1-2):276-89.
- [9] Hirsch KK, Bauer K, Scheck-Wenderoth M. Deep structure of the Western South African passive margin results of a combined approach of seismic, gravity and isostatic investigations. Tectonophysics. 2009;470(1–2):57–70.
- [10] Kaban MK, Tesauro M, Cloetingh S. An integrated gravity model for Europe's crust and upper mantle. Earth Planet Sci Lett. 2010;296(3-4):195-209.
- [11] Aitken ARA, Salmon ML, Kennett BLN. Australia's Moho: a test of the usefulness of gravity modeling for the determination of Moho depth. Tectonophysics. 2013;609:468-79.
- [12] Dupré S, Cloetingh S, Bertotti G. Structure of the Gabon Margin from integrated seismic reflection and gravity data. Tectonophysics. 2011;506(1-4):31-45.
- [13] Evariste NH, Genyou L, Tabod TC, Joseph K, Severin N, Alain T, et al. Crustal structure beneath Cameroon from EGM2008. Geodesy Geody. 2014;5(1):1–10.
- [14] Saleh S. 3D crustal and lithospheric structures in the southeastern Mediterranean and northeastern Egypt. Pure Appl Geophys. 2013;170:2037-74.
- [15] Tian Y, Wang Y. Inversion of the density structure of the lithosphere in the North China Craton from GOCE satellite gravity gradient data. Earth Planets Space. 2018;70:173.
- [16] Sampietro D, Mansi AH, Capponi M. Moho depth and crustal architecture beneath the Levant basin from global gravity field model. Geosciences. 2018;8:200. doi: 10.3390/ geosciences8060200.
- [17] Kaban MK, El Khrepy S, Al-Arifi N. Density structure and isostasy of the lithosphere in Egypt and their relation to seismicity. Solid Earth. 2018;9:833-46.
- [18] Geng M, Ali MY, Fairhead JD, Bouzidi Y, Barkat B. Morphology of the basement and Hormuz salt distribution in offshore Abu Dhabi from constrained 3D inversion of gravity and magnetic data. Tectonophysics. 2020;791:228563. doi: 10.1016/ j.tecto.2020.228563.
- [19] Ali MY, Watts AB, Searle MP, Keats B, Pilia S, Ambrose T. Geophysical imaging of ophiolite structure in the United Arab Emirates. Nat Commun. 2020;11:2671. doi: 10.1038/s41467-020-16521-0.
- [20] Thomas RJ, Ellison RA, Farrant AR, Goodenough KM, Kimbell GS, Newell AJ, et al. Geologic evolution of the United Arab Emirates over six hundred million years of earth history. Keyworth, Nottingham: British Geological Survey, Ministry of Energy, UAE; 2014.
- [21] Stern JR, Johnson P. Continental lithosphere of the Arabian plate: a geologic, petrologic, and geophysical synthesis. Earth-Sci Rev. 2010;101:29-67. doi: 10.1016/j.earscirev.2010.01.002.
- [22] Ali MY, Fairhead JD, Green CM, Noufal A. Basement structure of the United Arab Emirates derived from an analysis of regional gravity and aeromagnetic database. Tectonophysics. 2017;712–3:503–22.
- [23] Geosoft. http://updates.geosoft.com/downloads/files/how-to-guides/Target_Seeker.pdf; 2019.

- [24] Tapley B, Ries J, Bettadpur S, Chambers D, Cheng M, Condi F, et al. GGM02 - An improved Earth gravity field model from GRACE. J Geodesy. 2005;79:467-78. doi: 10.1007/s00190-005-0480-z.
- [25] Saibi H. Microgravity and its applications in geosciences. Gravity book. Intech Edition. 2018. p. 41-72. Chapter 3. doi: 10.5772/intechopen.71223.
- [26] Saibi H, Amir G, Mohamed FS. Subsurface Structural mapping using gravity data of Al-Ain region, Abu Dhabi Emirates. Geophys J Int. 2019;216:1201-13. doi: 10.1093/gji/ggy489.
- [27] Miller HG, Singh V. Potential field tilt a new concept for location potential field sources. Appl Geophys. 1994;32(2-3):213-7.
- [28] Cordell L. Gravimetric expression of graben faulting in Santa Fe Country and the Espanola Basin, New Mexico. New Mexico Geol Soc Guidebook, 30th Field Conf; 1979. p. 59-64.
- [29] Cordell L, Grauch VJS. Mapping basement magnetization zones from aeromagnetic data in the San Juan Basin, New Mexico. In: Hinze WJ, ed., The utility of regional gravity and magnetic anomaly maps. Soc Explor Geophys; 1985. p. 181-97.
- [30] Phillips JD. Processing and interpretation of aeromagnetic data for the Santa Cruz Basin Patahonia mountains area. South-Central Arizona: U.S. Geological Survey Open-File Report 02-98; 1998.
- [31] Roest W, Verhoef J, Pilkington M. Magnetic interpretation using 3D analytical signal. Geophysics. 1992;57:116-25.
- [32] Li Y, Oldenburg DW. 3D inversion of magnetic data. Geophysics. 1996;61(2):394-408.

- [33] Li Y, Oldenburg DW. 3D inversion of gravity data. Geophysics. 1998;63(1):109-19.
- [34] MacLeod IN, Ellis RG. Magnetic vector inversion, a simple approach to the challenge of varying direction of rock magnetization. Proceedings in 23rd international geophysical conference and exhibition, 11-14 August 2013, Melbourne, Australia; 2013.
- [35] Geosoft. Oasis montaj how-to guide, VOXI Earth modelling running an inversion, 13 pages. http://updates.geosoft.com/ downloads/files/how-to-guides/VOXI-How-To_Run_an_Inversion.pdf; 2013.
- [36] Toushmalani R, Saibi H. 3D gravity inversion using Tikhonov regularization. Acta Geophys. 2015a;63(4):1044-65.
- [37] Toushmalani R, Saibi H. Fast 3D inversion of gravity data using Lanczos bidiagonalization method. Arab J Geosci. 2015b;8:4969-81. doi: 10.1007/s12517-014-1534-4.
- [38] Ali MY, Watts AB, Farid A. Gravity anomalies of the United Arab Emirates: implications for basement structures and infra-Cambrian salt distribution. GeoArabia. 2014;19(1):143-58.
- [39] Thomas RJ, Ellison RA. Geological evolution of the United Arab Emirates, over six hundred million years of Earth history. Keyworth, Nottingham: British Geological Survey. United Arab Emirates Ministry of Energy, Department of Geology and Mineral Resources; 2014.
- Pilia S, Hu H, Ali MY, Rawlinson N, Ruan A. Upper mantle structure of the northeastern Arabian platform from teleseismic body-wave tomography. Phys Earth Planet Inter. 2020;307:106549. doi: 10.1016/j.pepi.2020.106549.