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Qualitative and quantitative analysis of the crust base structure using Kuwait gravity anomaly maps in the determination of new oil fields

Najeeb S. Aladwani*
Dept. of Earth and Environmental Sciences, Faculty of Science, Kuwait University
Corresponding author: Najeeb.aladwani@ku.edu.kw

Abstract

Kuwait state lies at the upper northeastern corner of the Arabian Plate, on the Arabian Gulf, and surrounded by Iraq from the north, the Arabian Gulf from the east, and Saudi Arabia from other sides. Kuwait settled on a thick sedimentary column built from the Permian age to recent; its thickness ranges between 7 and 8 km, take the form of the underneath basement structures. Detailed information has been got about the crustal basement structure under Kuwait state from the analysis of gravity anomaly maps and its consequential depth maps. The Geosoft Oasis Montaj software is used for preparing the geologic cross-sections from the modeling of the gravity profiles. The modeled cross-section provided us with the depth and structures of crustal basement rocks within 6 to 7 km under Kuwait and its associated sedimentary basins with a detailed geometry. We got considerable information about the sedimentary basins' geometry in Kuwait, such as the locations, extension, depth, and dimensions of the basins. This information coincides with Kuwait's oil fields location map. However, this information can be confirmed accurately from an aeromagnetic survey recommended carrying out the Kuwait region.

Keywords: Crustal basement depth; geologic cross-section; Gravity anomaly; Oil exploration; Kuwait

1. Introduction

We poorly understood the oldest basement rocks under Kuwait sedimentary succession due to the high thickness of that sedimentary column (Bou-Rabee & Niazi, 1991). In the early 1960s, a deep well in the Burgan oil field has been drilled to the depth of 13,853 foot and only reached the rocks which dating to the Triassic with facies of limestone, shale, marl, and anhydrite (Milton, 1967; Bou-Rabee, 1986; Bou-Rabee & Blakely, 1993; Warsi, 1990). The interpretation of Bouguer and free-air gravity anomaly maps and driving geologic cross-sections from the modeling of the gravity profiles can give us information about the crustal structure and deep subsurface geology of Kuwait. This method depends on detecting lateral changes in gravity related to subsurface rock density, where positive gravity anomalies indicate anomalous high-density bodies. However, the lack of knowledge about the rocks' density led to predicting the density depends on the depth and rock types. Thus, the crustal basement structure models can be produced by fitting the model with the gravity profiles as closely as possible (Hussein & El-Mula, 2017).

Hosseini *et al.* (2013) detect the edge of the Gheshm sedimentary basin in the Persian Gulf in Iran from the gravity anomaly map using horizontal and vertical derivative filters. They also succeeded in highlighting the fault pattern and lineaments. Also, Altinoglu *et al.* (2015) extract the analytic signal (AS) depth maps from the Bouguer anomalies map over the Denizli Basin of western Anatolia region and define four lineaments. The resulted lineaments coincided with the active fault map in the region and found a good agreement between them.

This study focuses on interpreting the gravity anomaly data covering the country to give new qualitative and quantitative information about the crustal structure, subsurface geology, and sedimentary basins. In this study, two gravity anomaly maps of Kuwait were used, a free-air gravity anomaly map and a Bouguer anomaly map; The Bouguer map was reduced to a density of 2.67 g/cm^3. An interactive Geosoft Oasis Montaj software v.8.4 (2009) was used to model the gravity profiles.

We discussed our results in the context of the geological tectonic that controls the formation and the accumulation of sedimentary basins in Kuwait comprehensively and systematically. Also, we proposed a depth model that obtains the geometric distribution of the basins and underlying basement rocks.

1.1. Location

The State of Kuwait is situated at the northeastern corner of the Arabian Peninsula (Figure 1), at the northeastern corner of the Arabian Peninsula, on the western coast of the Arabian Gulf. It covers about 17,600 km^2 extending between latitudes 28^o 30' N and 30^o 05' N and between longitudes 46^o 33' E and 48^o 33' E. The north-south length of Kuwait is about 200 km, and the width from the Arabian Gulf's coast to in the east to Iraq's borders in the west is about 170 km.

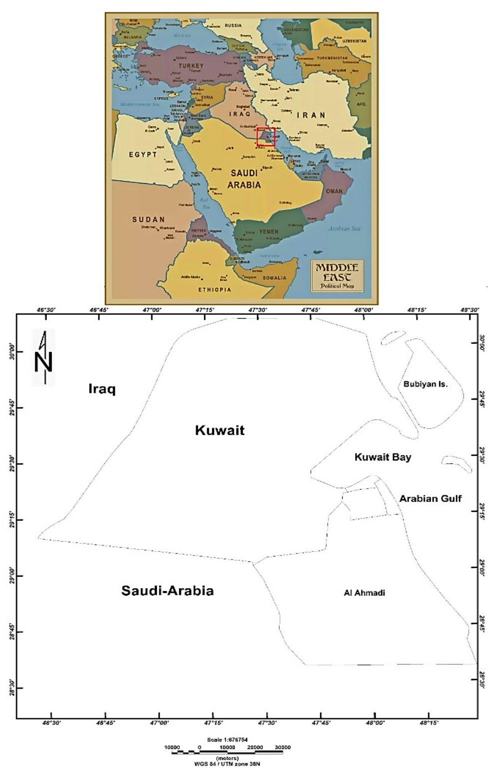

Fig. 1. Location map shows Kuwait state and its borders from all sides.

1.2. Topography

Kuwait is a desert with low to moderate relief. Its topographic surface rises gently from the shoreline of the Arabian Gulf toward the southwest, the elevation of the surface relief ranges between -20 m at the northeast and 300 m in the southwest corner (Figure 2). Khalaf *et al.* (1984) divide the Kuwait physiographical to Al-Dibdibba gravel province, which occupies most of the northern part of Kuwait, which bordered Iraq. This province is characterized by north-east parallel gravel-capped ridges that rise a few meters above the surface.

The second province is a flat-sand province that covers the Al-Ahmadi area in the southern half of Kuwait, is featureless and nearly flat except for some 40 m height-hills. The third physiographical division is the Jal Az-Zor hills which reach 120 m in height and extend along the northern coast of Kuwait Bay. Also, Al-Ahmadi ridges are similar to Jal Az-Zor hills, but it extends parallel to the southern shoreline. The last division is sand-flat areas, which lie in northeastern Kuwait and has several offshore islands and low-lying muddy shores, the largest of which is Bubiyan Island (Figure 2). Generally, Kuwait is fenced by a shallow marginal sea of the Arabian Gulf which leads to the topography of the surface is relatively monotonously flat to gently straight with low hills, scarps, valleys, and shallow wide inland depression (Al-Sulaimi & Al-Ruwaih, 2004; Al-Sulaimi & Pitty, 1995).

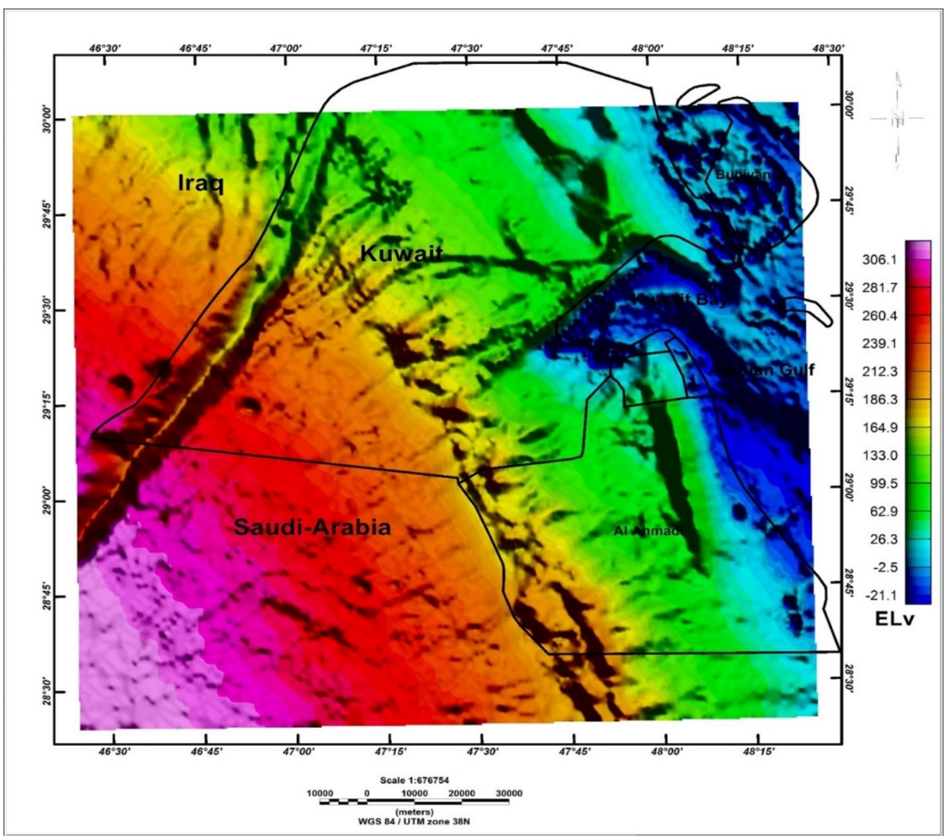

Fig. 2. Topographic elevation map of Kuwait shows the surface elevation.

1.3. Geological setting

1.3.1. Structural

The Arabian plate has a thickness of 40 km and runs on a transform fault with the Anatolian Plate to the east direction. It interacts divergently with African Plate forming the Red Sea and sinks under Eurasian Plate, resulting Zagros Fold-Thrust Belt from the east (Figure 3) (Stern & Johnson, 2010). The crustal basement is Precambrian rocks and exposed in the west of the Arabian Plate, forming the Arabian Shield (Wagner, 2011). Phanerozoic sediments and Cenozoic flood basalts formed sediments package overlaid the Arabian Shield, known as Arabian Platform (Al Hosani *et al.,* 2013; Bou-Rabee & Abdel-Fattah, 2004). This sedimentary package includes carbonate and siliciclastic deposits with intermittent evaporates. They attributed the Arabian Shield exposure in the southwest and the thickening of the Arabian Platform towards the east to uplift from rifting of the Red Sea and subduction at the boundary with Eurasia.

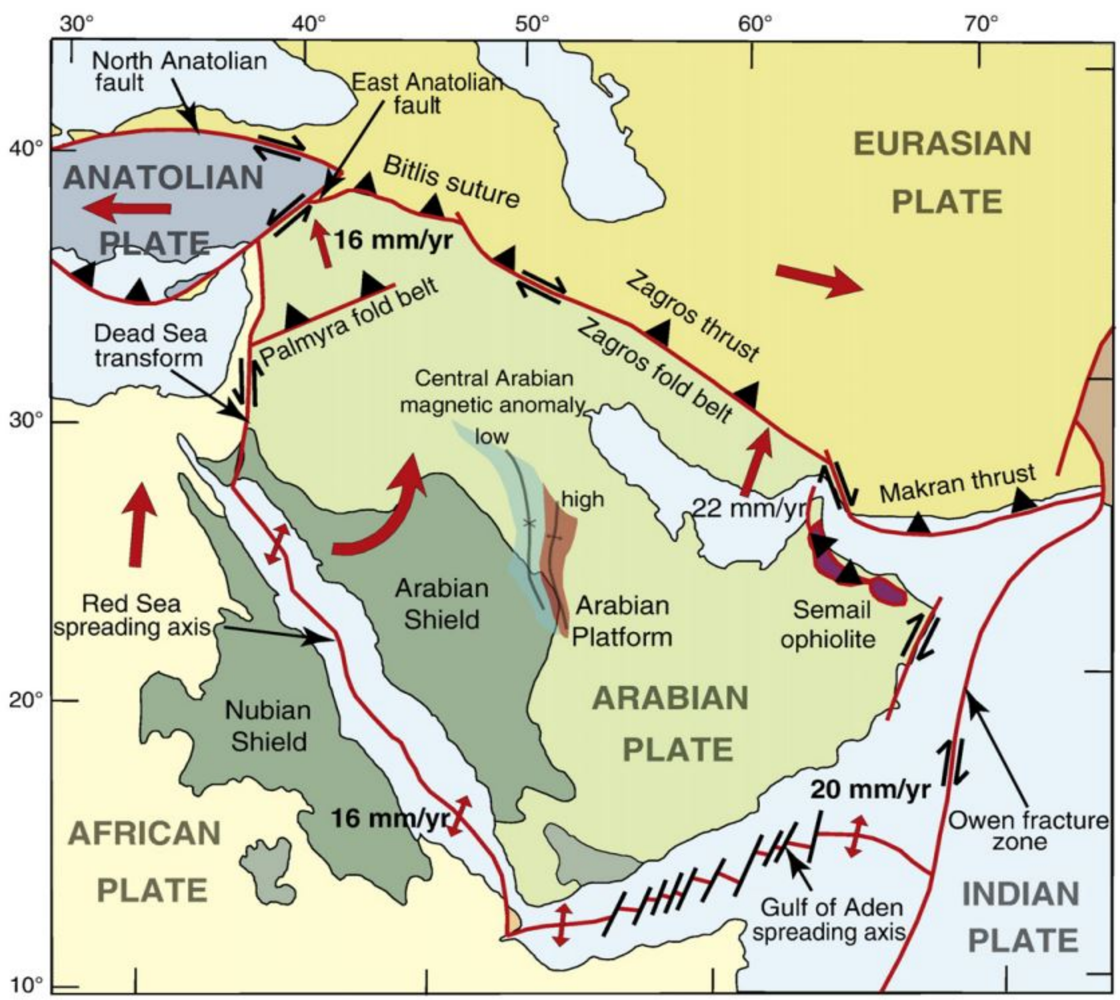

Fig. 3. Regional tectonic map shows the Arabian Plate tectonics and its interaction with African Plate, Eurasian Plate, and Anatolian Plate, and shows the location of Zagros fold belt (after Johnson and Stern, 2010).

Kuwait lies on the west flank of the Arabian Gulf geosyncline and the eastern foreland of the Arabian Sheild. The basement structures activated in various geological periods from Jurassic to the Paleogene. Due to the uplifting of the basement, the overlying sedimentary cover is also uplifted, domed, and faulted, successively producing growth structures (Wagner, 2011). The significant aquifer of the Dammam Formation has been brought near to the surface. The structures produced from the uplift, faulting, and tilting of the Arabian Plate lead to the tilting of the sedimentary cover overlaying the basement, producing the well-known northwest-trending scarp land of Arabia (Stern & Johnson, 2010). During such uplift, the continental slope toward the northeast developed, creating a drainage trend to the northeast, which leads to the deposition of the fluvial deposits of the Dibdibba Formation in the northeast depression. The evidence shows that the structures have uplifted due to horizontal compression, especially during pre-Miocene times (Bou-Rabee, 1996).

1.3.2. Stratigraphy

The Kuwait area is a part of the Arabian Peninsula where the rocks range from upper Permian age to recent (Mukhopadhyay *et al*., 1996), with a thickness ranges between 23,000 ft and 27,000 ft. However, The strata below the upper Permian strata are updated Pre-Kuff sediments interpreted as late Devonian to Permian age (Figure 4) (Bou-Rabee, 1986). The deep well that has drilled in the Burgan oil field reached the Triassic age and found that it includes limestone, shale, marl, and anhydrite. These rocks overlined by 4500 ft of Jurassic limestone and 1300 ft of anhydrite. A thick sediment section of Cretaceous rocks ranges between 6000 and 10,000 feet thick, followed by the Jurassic rocks. The upper Cretaceous is composed of thick limestone, interbedded by marls and thin shales. This limestone extends into the upper part of the middle Cretaceous section. Next, the lower part of the middle Cretaceous and most of the Lower Cretaceous is generally sandstone, with intervening shale horizons and at least two well-developed limestones (Bou-Rabee, 1996). The sedimentary succession ends by 3500 feet thick of Cenozoic rocks, which comprises limestone and evaporite (Rus formation). Also, the Kuwait Group is included in Cenozoic sediments and is composed mainly of clay sandstone (Al-Sulaimi & Mukhopadhyay, 2000; Murris, 1980).

2. Methodology

2.1. Topographic elevation mapping

The topographic elevation map is a 2D/3D digital map represent the terrain's surface-commonly for the area of study, created from terrain elevation data. It is satellite elevation data widely used in many research fields, including geology, hydrology, and geomorphology studies, to understand spatial relationships of structures (Ganas *et al*., 2005; Picotti *et al*., 2009; Al-Dousari & Al-Awadhi, 2012; Al-Dabsheh & Odeh, 2019; Khalaf & Al-Zamel, 2018; Sheng, 2019; Ameen *et al*., 2020; Adesola *et al*., 2017; Ehsan *et al*., 2018). The topographic map was created from the elevation data that have been obtained from Bureau Gravimetrique International (BGI). The surface topography of Kuwait is flat and slightly increase in height from MSL at the eastern coast on the Arabian Gulf to 300 m height above sea level at the southwestern corner of the country (Figure 2). The gravity data has been reduced to Mean Sea Level (MSL) to avoid the topographic error at creating the geologic 2D model.

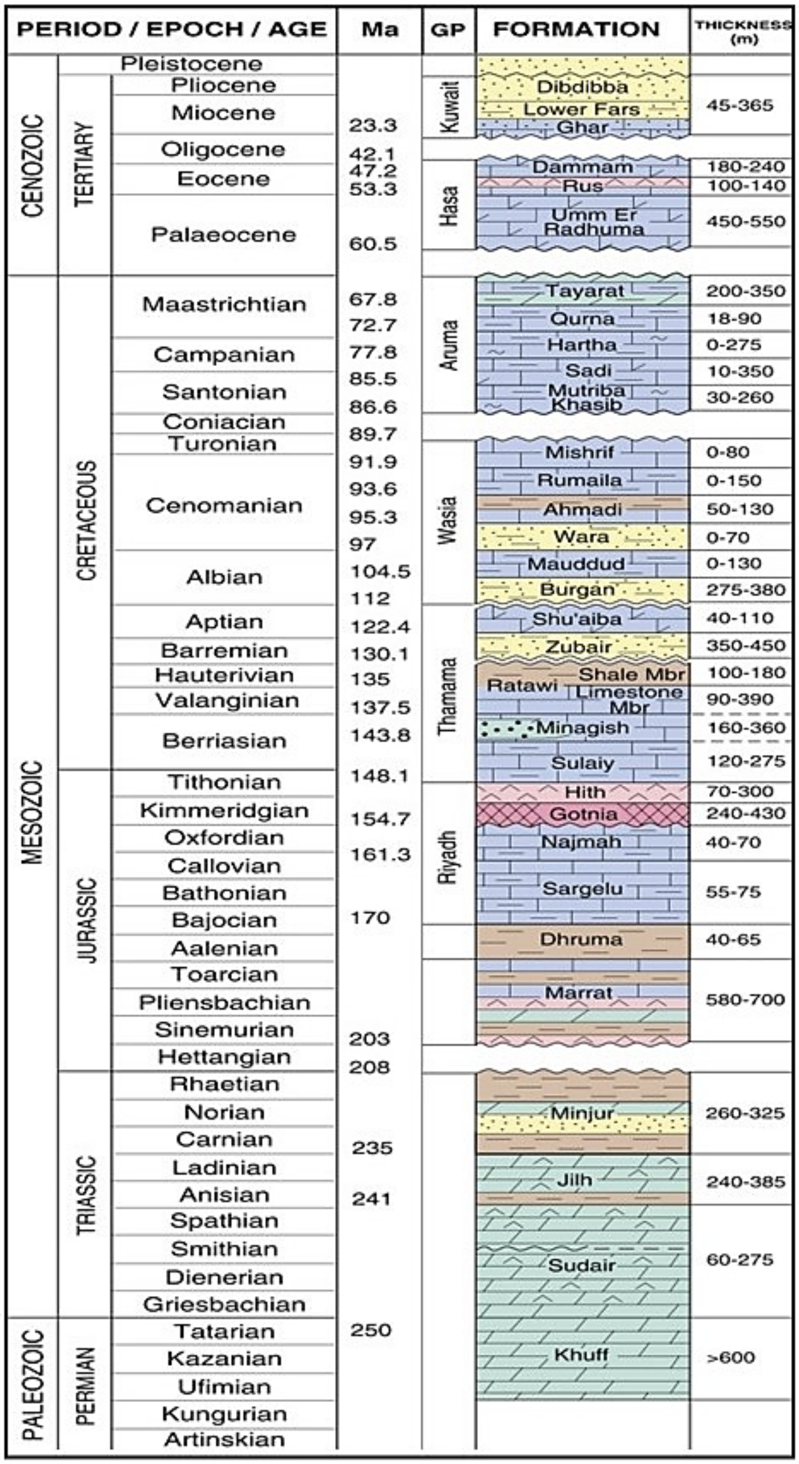

Fig. 4. Generalized stratigraphic column of Kuwait (Abdulla *et al.*, 2005)

2.2. Gravity data

It has brought the set of data used in this section from Bureau Gravimetrique International (BGI). This data collected in 1962 by the International Union of Geodesy and Geophysics (IUGG) Institute of Geophysics, Tehran University, under the project titled "Establishment of Gravity Bases in the Persian Gulf." The Free-air map reflects the topography of the study area; its intensities range between 3 and -44 mGal and increase both southward and westward (Figure 5.B). Also, the Bouguer map of Kuwait is prepared using a reduction density of 2.67 g/cm^3, its values vary from -16 mGal in eastern Kuwait to -46 mGal in the northern part of Kuwait near the Iraq border (Figure 5.A).

2.2.1. Gravity data processing

Fast Fourier Transform technique (FFT)

The Geosoft Oasis Montaj package V.8.4 has used the Fast Fourier Transform (FFT) was applied on the gravity data to calculate the energy spectrum where converts data from the time domain to the frequency domain. Through this technique, the average depths to gravitational sources could be estimated by the following formula:

$H = -slope/4\pi$

Where:

H: Depth (km)

Slope: The slope of the energy (power) spectrum

4π: constant

Gaussian Residual/Regional Filter

We apply the Gaussian filler technique in this study. It designed the separation procedures to produce two separated gravity maps; the first one is the residual gravity map that refers to shallower variations, while the second one refers to more profound variation, "i.e., regional" gravity anomalies. In other words, the measured gravity map is divided into two parts, the residual and the regional component maps (Ali, 2009).

Depth estimation.

The analytic signal (AS) can be applied either in space or frequency domain, generating a maximum directly over separated bodies and their edges and created through the vertical and horizontal gradients combination of the gravity anomaly (Ansari and Alamdar, 2009). The analytic signal (AS) filter has been used for edge detection and depth estimation of gravity and magnetic bodies by several authors, e.g., Roest *et al*. (1992), who applied it for detecting causative body location, while Hsu *et al*. (1996) used it for geologic boundary edge detection. The analytic signal (AS) is producing from getting the first derivative in x, y, and z directions and calculating the square root of the sum of their squares. We estimated the gravity source depths using the gravity method from the ratio of the gravity field Analytic signal (AS) to the vertical derivative analytic signal (AS1) of the gravity field (Figure 6). Another way to calculate the depth of the gravity anomalies is the Source Parameter Imaging (SPI) function, which is a quick, easy, and robust method for calculating the depth of gravity anomalies (Figure 7) (Thurston & Smith, 1997).

2.2.2. 2D Geologic cross-section

The 2D geologic model has been created and corrected by comparing the cross-section with the gravity response to the different geologic units. It imagines the horizontal variation in the subsurface along the basement surface and the rock types composed in the investigated area. In addition to that, this technique can determine the depths to the basement surface and confirm the results obtained by the depth estimated maps.

These geological models reaches to a depth of about 9,000 m from the surface; the basement-sedimentary contrast line was adjusted at a depth of 5000 m from the surface. The thickness of different rock units and the contact between the different ages deposits and the literature depth of basement extracted from the previous gravity studies which relevant to this study about Kuwait such as Bou-Rabee (1986), Bou-Rabee and Blakely (1993) and Warsi (1990).

3. Results and discussion

The qualitative interpretation of Kuwait's crustal structure and subsurface geology was obtained from the observed and corrected Bouguer and the Free-air maps. The difference in gravity values between the two maps is low in the north and along the Arabian Gulf coast due to the low elevation of the topographic surface from MSL (Figure 2 and Figure 5), while this difference increase in the southwest and the west because of the topographic surface elevation which reaches to 300 m in the southwest corner of Kuwait. The Bouguer map corrected from the effect of this elevation's mass on the observed values of gravity. The Free-air map shows intensities range between 3 and -44 mGal, where the maximum values are found in the south and the west. A gravity high may reflect a small anticline found near the south border of Kuwait in the south of Al-Ahmadi province (Figure 5.B).

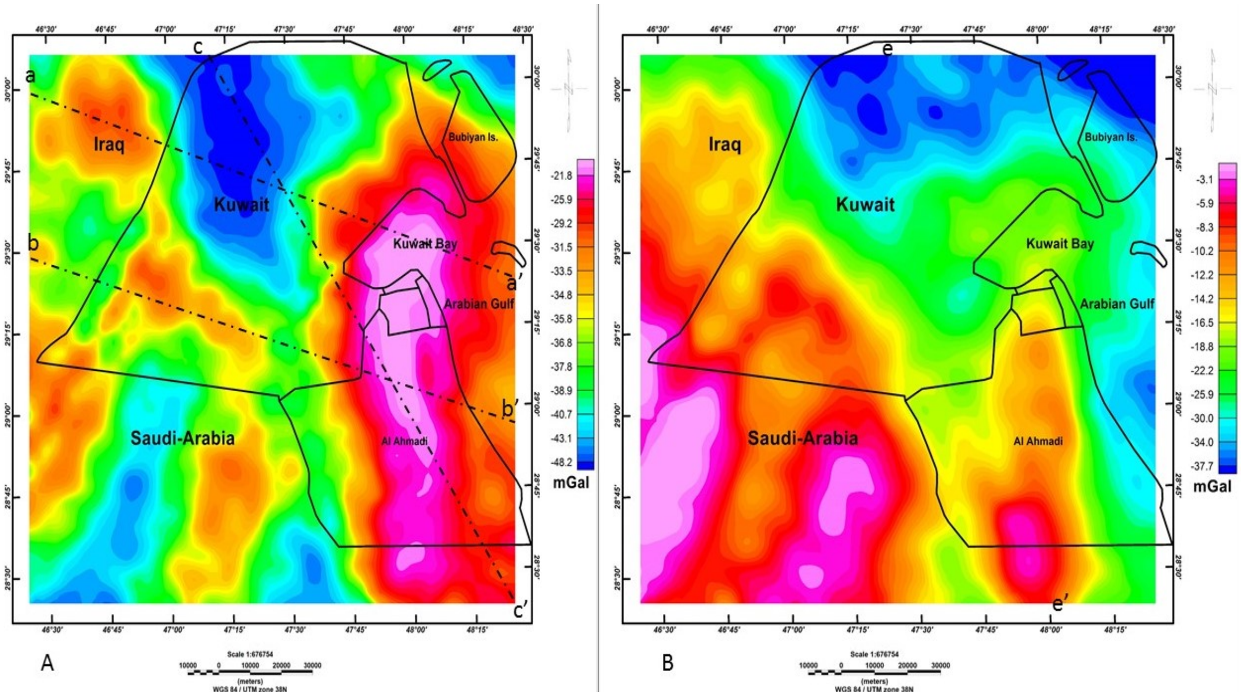

Fig. 5. Gravity anomaly maps; A) The Bouguer map, corrected from the excess mass of the topography above the mean sea level, B) The Free-air map corrected to the datum of mean sea level without the consideration of the mass of surface elevations. The gravity profiles were used in the 2D geologic cross-section were drawn on A.

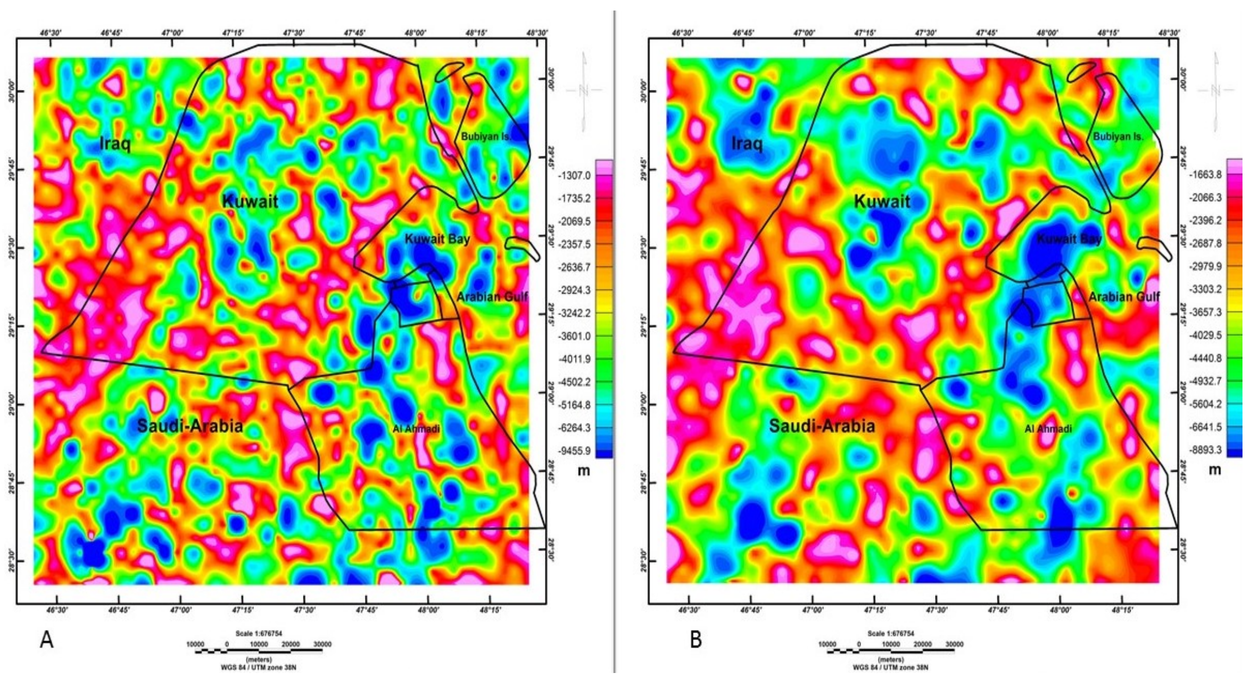

Fig. 6. Crustal basement depth maps generated from the analytical signal (AS) of the gravity anomalies values are divided by its first vertical derivative; A) Generated from the Bouguer map, B) Generated from the Free-air map.

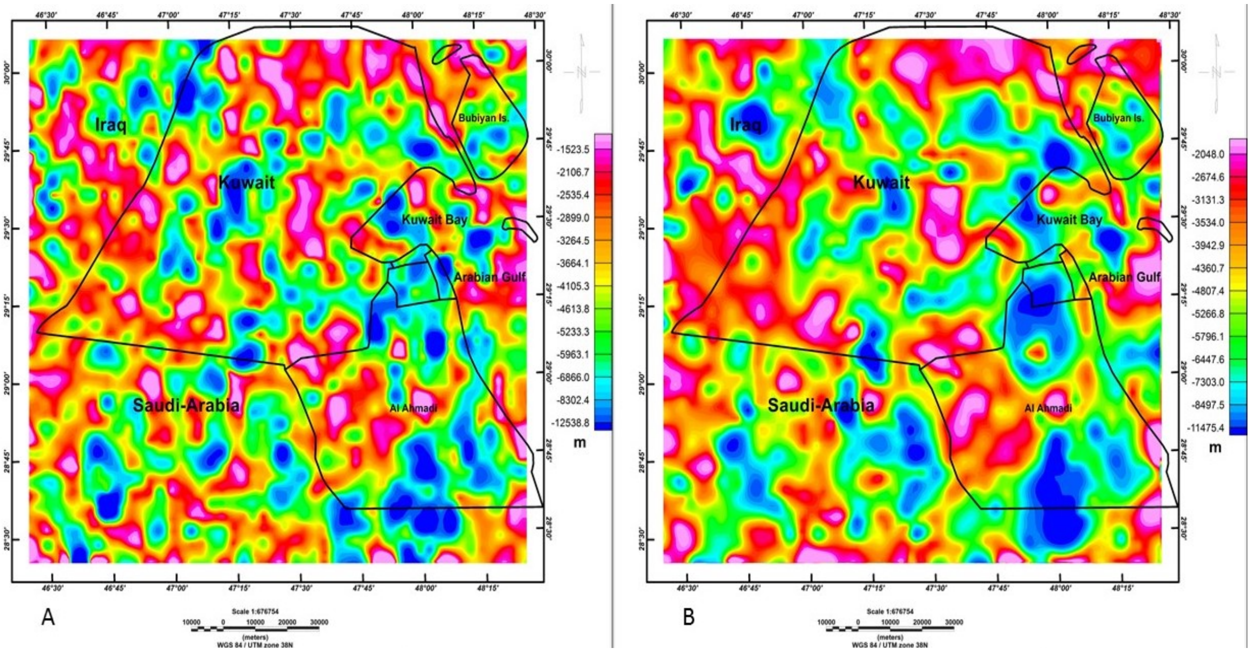

Fig. 7. Crustal basement depth maps generated fromSPI module in Geosoft® software applied to gravity anomalies values; A) Generated from the Bouguer map, B) Generated from the Free-air map.

The Bouguer map shows intensities range between -16 and -46 mGal and reaches their minimum values at the northern part of the state near the Iraq border, while the maximum gravity values found in Al-Ahmadi province and along the western border on the coast of the Arabian Gulf, under Kuwait Bay. The long positive anomaly that extends from the south to the north and the Kuwait coastal border (Figure 5.A) may result from a series of crustal anticlines. These anticlines are known as Kuwait arc, consider a crustal basement anticlines series extent north-south. Basement depressions surround it from the east under Arabian Gulf and from the west under the intra-shelf basins covering most of Kuwait where all oil fields are found, such as (Raudhatain, Ratqa, Dharif, Umm Gudair, and Wafra). The characteristics of this positive anomaly are not coinciding the topographic relief of the Ahmadi ridge. However, the anomaly is shifted nearly 10 km to the west. Another positive anomaly was found on the Bouguer Map (Figure 5) at the southern border of the northern sector of Kuwait and had a gravity value of -27 mGal and width about 75 km above Dibdibba Arc (Warsi, 1990).

The low intensity of gravity values refers to low-density sedimentary rocks, and the shape of the low-gravity anomaly is a function of the geometry of the basin. The Bouguer map shows three suggested sedimentary basins; the first one is a gravity low in southwest Kuwait indicates the presence of a small basin of low-density sedimentary rocks that may extend into Saudi Arabia. The second is another small low-density sedimentary basin in the west of Al-Ahmadi province and the extent to Saudi Arabia. The third and most extensive sedimentary basin in Kuwait is the Dibdibba low anomaly found in the north of Kuwait, above Dibdibba Basin, which extends in most of the northern sector of the Kuwait desert and a small area of southern Iraq.

The basement depth maps were estimated from the analytic signal (AS) of the Bouguer and the Free-air maps and its first vertical derivative (Figure 6), and also the depth was estimated from the SPI module, which derives the first derivative in x, y, and z directions and give us the tilt derivative grid (Figure 7). The estimated depth from the analytic signal (AS) ranges between -1200 m and -9500 m on the Bouguer anomaly map (Figure 6.A) and between -1500 m and -9000 m on the Free-air map (Figure 6.B), while the estimated depth from SPI module ranges between -1500 m and -12,000 m on both gravity maps (Figure 7). The comparison between the different basement depth maps and the oil fields location in Kuwait has found that the depressions in analytic signal depth maps (Figure 6) are equivalent to the oil field locations (Figure 8) (US. Energy Information Administration (2016) may give us a high probability of founding small sedimentary basins under these depth anomalies. The northern oil fields found in the Dibdibba Basin are equivalent to the blue closures in north Kuwait in figure 6. Also, the oil fields found in the north of Al-Ahmadi province and Kuwait Bay lie in the same sedimentary basin, represents a geosyncline extending from the Arabian shield on the west to the complexly folded and faulted Zagros Mountains on the east, and equivalent to the blue closures that found in this area in figure 6.

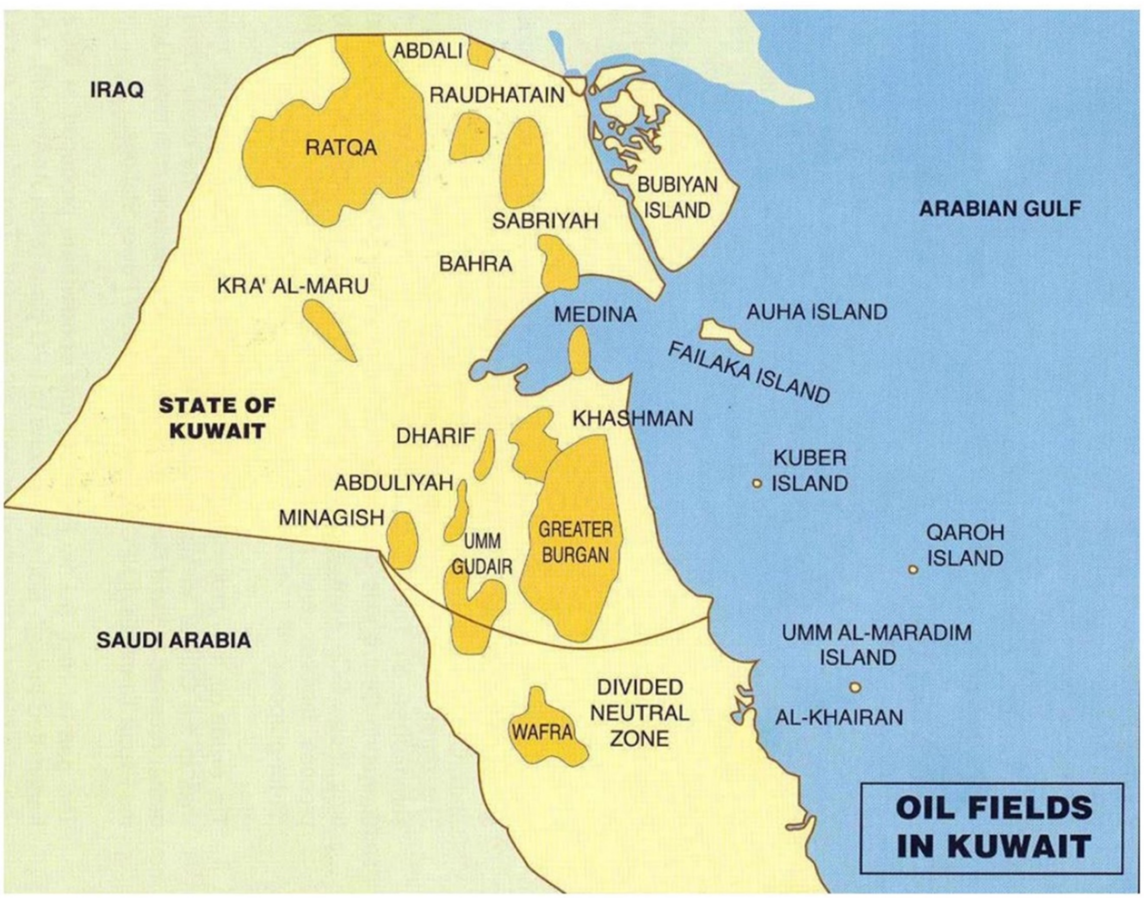

Fig. 8. Oil fields location map of Kuwait (US Energy Information Administration, 2016)

Three geologic cross-sections were made from the Bouguer map using computer modeling of gravity profiles that extend across Kuwait (Figure 5.A and Figure 9). The cross-sections were modeled to depths of nearly 6 km, which is adequate to represent middle to upper Paleozoic and Mesozoic succession throughout Kuwait. The density that used for this modeling is 2.5 g/cm^3 as an average for sedimentary rocks and 2.75 g/cm^3 as an average for the basement rocks. We consider the density values only the first approximation due to the lack of density measurements and estimated for this study, depends on the rock types and depth of burial. The modeling of geologic cross-sections guided by the data of the well that drilled in the Burgan field and defined the contact between Cretaceous and Jurassic beds, and defined the top of Triassic and its bottom. Also, it is guided by the previous studies of Milton (1967), Murris (1980), Yousif and Nouman (1997), Ali (1995), and Wilson (1984).

The resulted three profiles provide qualitative and quantitative information such as dimensions of the basements and their approximate depth along with the profiles. The first two profiles (aa' and bb') are parallel and extend for 220 km from the northwest part of Kuwait to southeastward, where Kuwait Bay was found. These two profiles include the minimum gravity values at the northwestern ends, which reach -48 mGal, and the maximum gravity values at the other ends that reach -16 mGal over Kuwait Bay. The third profile (cc') extends from the northwest of Kuwait over Dibdibba Basin, where the gravity value reaches -48 mGal, to Kuwait's southeast over Al-Ahmadi province the gravity value reaches -20 mGal (Figure 5.A and Figure 9).

The profile (aa') shows the basement anticline of Kuwait Arc at the right side of the section at a depth of about 4 km, and also shows another anticline at the left side of the section under Iraq's land depth increase a bit of 4 km. The geosyncline lies between the two anticlines under Dibdibba Basin, with a sedimentary column reaching 6 km depth. The profile (bb') shifted about the Dibdibba geosyncline but still under Kuwait Arc, where it obtained at a depth ranges between 5 and 6 km. The profile (cc') passed through two specific features; Dibdibba Basin and Kuwait Arc, but in a north-south direction, most of it passes over Kuwait Arc positive closure, and shows that the depth of the anticlines is 5 km at the south and increase toward the north, while the Dibdibba Basin increase in depth about 6 km toward the north. The Bouguer map and the geologic profiles give us the ability to determine the geometry of the basins, such as the Dibdibba Basin that covers 43 km width (E-W) and 60 km long (N-S) in Kuwait's land with more extension in Iraq, the depth of the basin ranges between 5 km at the margins and about 7 km in the deepest point in the basin.

4. Conclusion

This study provides a qualitative and quantitative interpretation of the Free-air and the Bouguer maps for the crustal basement structure in Kuwait. The physical properties of the crustal basement rocks could only be approximated because of the absence of drilled wells that reached the basement. The resulted 2D geologic cross-sections have enhanced our interpretations of the stratigraphy and structure of the upper 5-6 km of the crust. These sections show that all oil fields in Kuwait lie in the geosyncline between two anticlines; Kuwait Arc and Dibdibba Arc anticlines. This geosyncline contains the thick sediment section, which characterizes this region. The resulting depth maps provided information about the locations, depth, and geometry of the sedimentary basins under the Kuwait region, which coincided with Kuwait's oil field's location map.

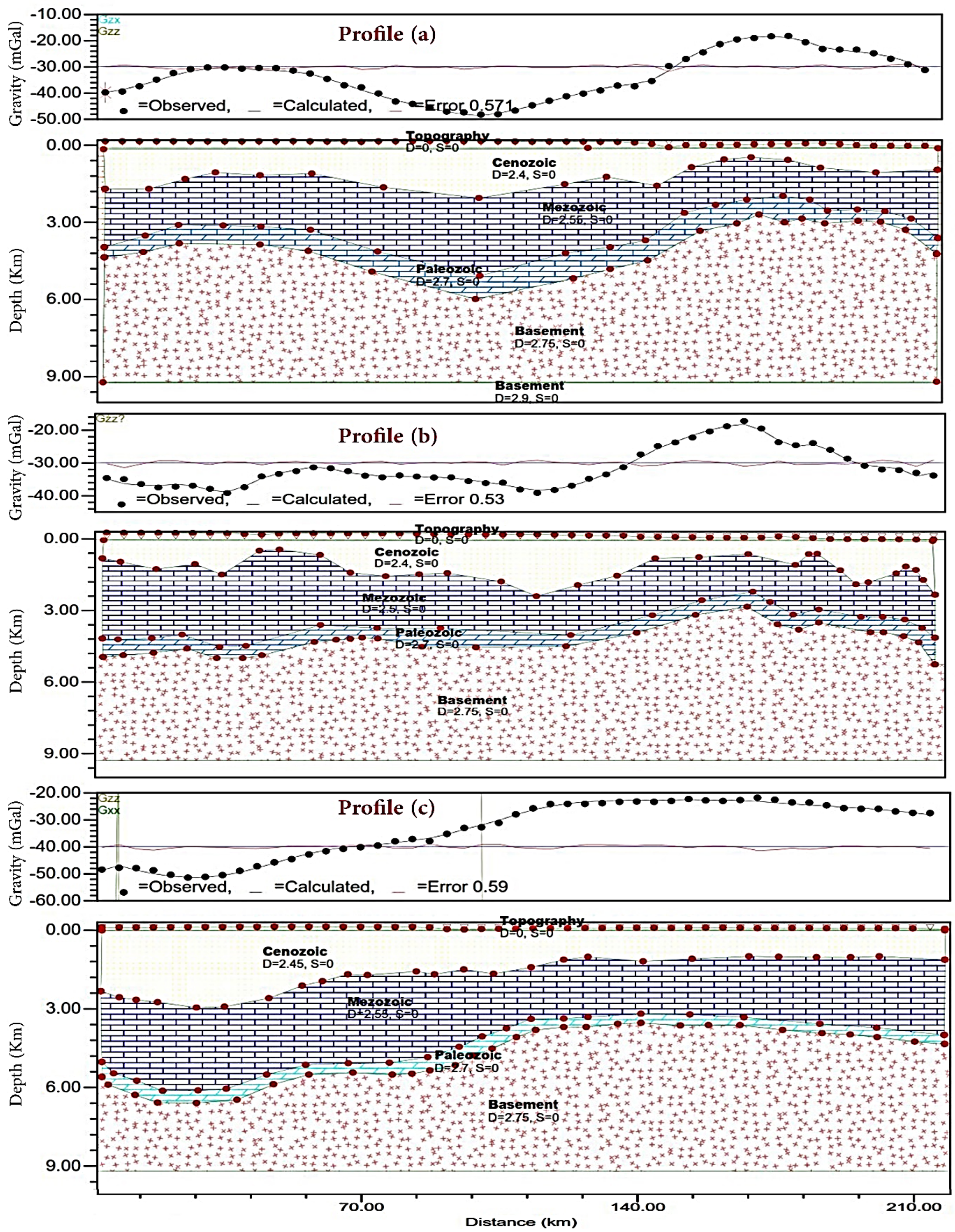

Fig. 9. The geologic cross-sections derived from gravity profiles (aa', bb', and cc') that have been drawn on the Bouguer map in Figure 5.

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