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Identification of Subsurface Geological Structures from Gravity Data by Modelling Techniques in Kalak-Bardarash Area, West of Erbil City Iraqi Kurdistan Region

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Abstract

A quantitative interpretation of gravity anomalies in the Kalak-Bardarash area, west of Erbil City in the Kurdistan Region of Iraq, was performed using two-dimensional analysis techniques. These techniques modeled geological structures identified from a previously created Bouguer anomaly map of the area. Five profiles were selected for the analysis, resulting in eight models constructed for both deep and shallow-seated rock units. The deep-seated rocks are represented by the basement rocks, with models constructed in the NNE-SSW, WNW-ESE, and NW-SE directions using the regional anomaly component. The depth of the basement rocks ranges from five to nine kilometers and is affected by numerous faults in the form of graben and step structures. The basement rock surface slopes towards the NE and ESE at a gradient of 110 m/km. The shallow-seated rocks are represented by the sedimentary cover, which includes Neogene, Paleogene, and Cretaceous-aged groups of formations. The residual component of the anomalies of the five profiles were interpreted. Three profiles, oriented NNE-SSW and nearly perpendicular to the main anticlinal structure, revealed that the Bardarash anticline is influenced by two faults striking both limbs and extending in the NNW-SSE direction, with an estimated throw of 200 meters on each side. The southern fault is believed to extend down to the basement rocks. The other two profiles, oriented NW-SE and nearly perpendicular to the Zab River, indicated the presence of two additional faults with a throw of approximately 600 meters in the deeper parts striking the basement rocks, dipping towards the southeast. The throw of these faults gradually decreases upward in the sedimentary cover, reaching about 200 meters. These faults directly influence the course of the Zab River, directing it in a NE-SW direction at this district.

1. Introduction and Study Area Location

The subject of gravity exploration in applied geophysics is concerned with the study of the subsurface through measuring their gravity effect with appropriate measuring devices called gravimeters on the surface. A gravity survey was conducted in the area around Kalak and Bardarash towns from which Bouguer anomaly map was constructed by Salaee (2015). This map gives indications of the structural picture of the subsurface since rocks have variable densities, whereby the low-density rocks show lower gravity values. In case of the upward arching of the higher density rock formations in a structural high, as in the case of an anticline, the earth's gravitational field will be higher directly over the axis of the structure than along its flanks (Dobrin and Savit, 1988). The major aim of any geophysical survey is to detect the underground geology by determining its lithology, stratigraphy, and structure.

The area of study is located in the Northwest of Erbil city in Iraqi Kurdistan Region and defined by Zone 38 which has the coordinates; 4008700 – 4049900N and 365550 – 399400E. It covers about 1400 Km2 (Figs. 1, 2 and 3A). The main objective of this study is to add a quantitative analysis for the Bouguer anomalies which were analyzed qualitatively previously by Ghaib and Salaee (2021). The national Bouguer anomaly maps of Iraq did not cover some areas of the country for different reasons. One of the main objectives of this study and the previous one, other than delineating the subsurface structural features, is to survey gravimetrically an area which is within these un-surveyed gaps. Many authors tried to fill some other gaps by regional or local gravity surveys such as Ghaib (2001) (2001), Ghaib et al. (2009), Ghaib and Al-Dawoody (2012), Al-Majid (2013), Mutib et al. (2020) among many others.

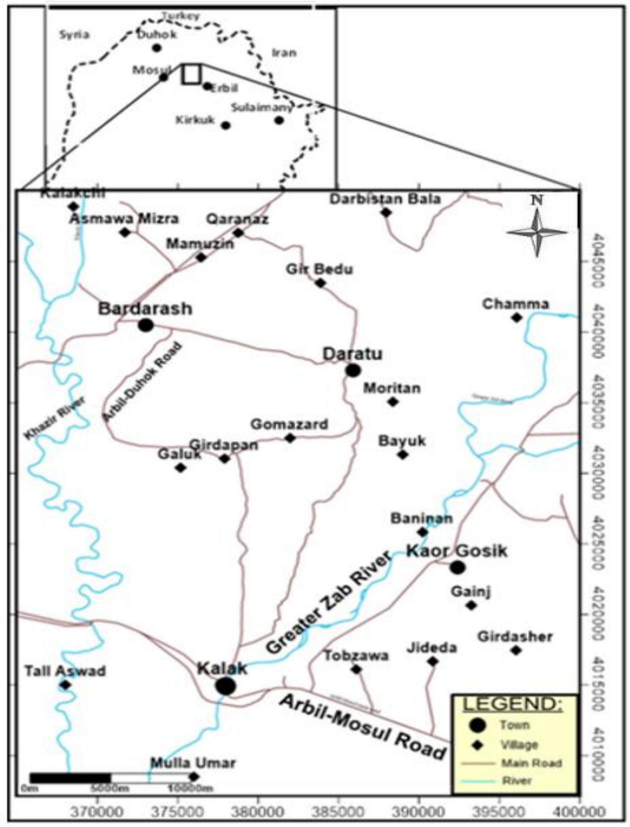

Figure 1: Study area location

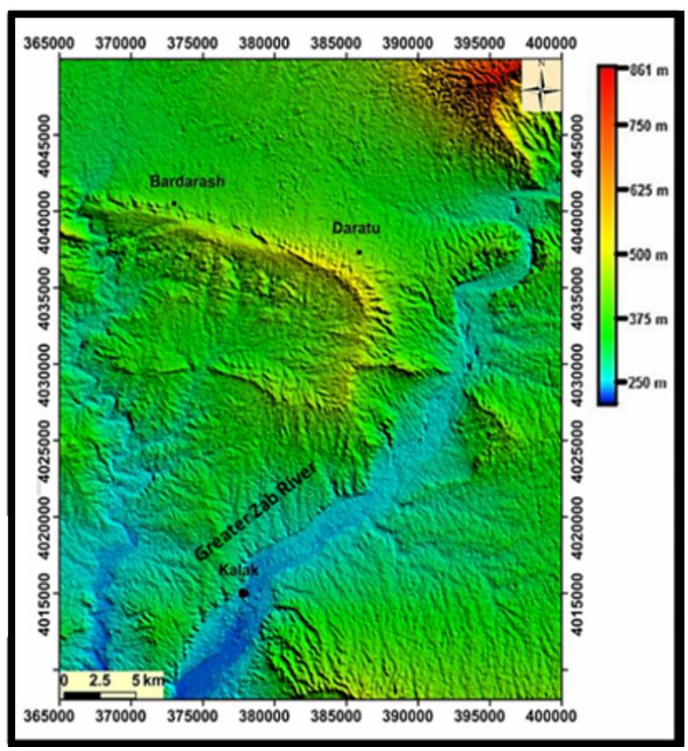

Figure 2: (DEM) image of the study area.

2. Tectonic and Geological Setting

Tectonically the area of study is within the Foothill Zone of Iraq (Numan, 1983, Jassim and Goff, 2006). The former author, through his study considered the Greater Zab River to be a tectonic boundary between two blocks. The Mosul block to the northwest of the river with folds almost trending ENE-WNW or even E-W (northwestern part of the study area), and the Kirkuk block with folds trending NW-SE (southeastern part of the study area).

Concerning surface geology, River Terraces cover most of the area represented by conglomerate, siltstone, sandstone, rock fragments, and silty and clayey soil, as shown in figure 3B. Table 1 gives brief lithological descriptions for the cropping out formations in and around the study area (Buday, 1980, Sissakian et al., 1997, Omar, 2005, Ghaib and Salaee, 2021).

3. Theory of Gravity Surveying

The gravity value measured in the field is the value which is the result of a combination between the first and second laws of Newton:

$F=G (m_1 m_2)/r^2$ and $F=mg$

Leading to:

$G=GM/R^2$

Where (F) is the force of attraction, (G) is the gravitational constant which is equal to 6.67x10-11m3kg-1s-2, (m1) and (m2) are two masses attracting each other, (r) is the distance between them, (g) is the gravity, which is measured by the gravimeter, (M) is mass of the Earth while (R) is its radius.

The resulting gravity value after some corrections is termed the Bouguer Anomaly, and a contour map, known as the Bouguer Anomaly Map, is generated from the corrected data. This map illustrates the lateral density variations in the sub-datum, offering insights into the structural characteristics of the subsurface. The theoretical foundation of gravity surveys is extensively covered in textbooks like Reynolds (2011), Gupta (2011) and Kearey et al. (2002).

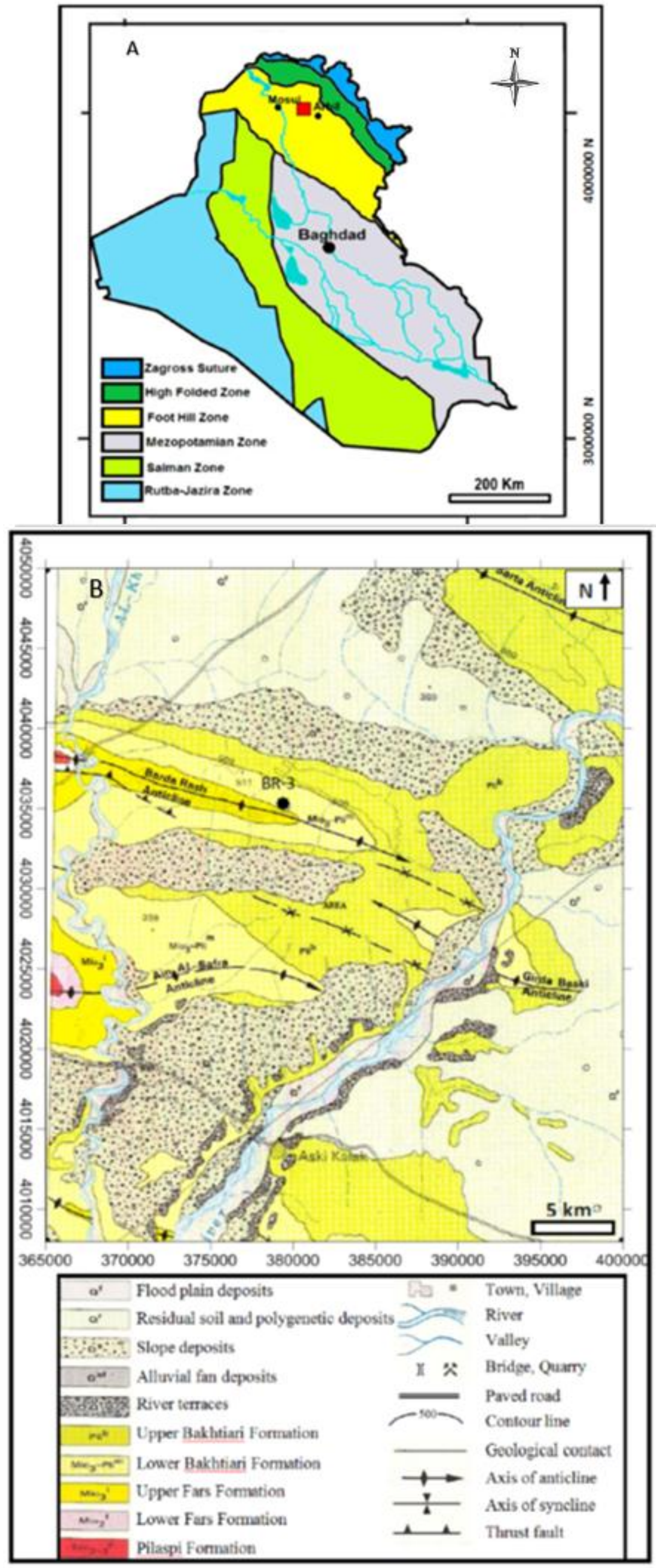

Figure 3: (A) Tectonic map of Iraq (Jassim and Goff, 2006) (B) Geological map of the study area (Sissakian et al., 1997).

Table 1: Rock formations cropping out in kalak-bardarash area

Formation Name	Lithology
PilaSpi Formation Age: Middle-Upper Eocene	Mainly crystalline and calcareous dolomite with minor amounts of clayey limestone.
Lower Fars (Fat'ha) Formation Age: Middle Miocene	Anhydrite, gypsum and salt, inter-bedded with limestone, marl, and relatively fine grained clastics.
Upper Fars (Injana) Formation Age: Upper Miocene	Cyclic clastic deposits exhibit an upward coarsening trend. Each deposition cycle is characterized by alternating layers of mudstone and sandstone. The mudstone occasionally contains silt, with intermittent thin layers of inter-bedded siltstone.
Lower Bakhtiari (Muqdadiya) Formation Age: Pliocene	Clastic cyclic deposits show a fining trend upwards, commencing with claystone, followed by pebbly sandstone, and culminating in thick layers of conglomerate.
Upper Bakhtiari (Bi Hassan) Formation Age: Pliocene	Molasses sediments represented by conglomerates and claystone with some sandstone and siltstone beds.

4. Materials And Methods:

4.1 Bouguer Anomaly Map

The main material of this study is the Bouguer anomaly map which its field data were originally collected by (Salaee, 2015). The overall gravity data error, during the collection and correction, was determined to be ±0.01 mGal, facilitating the creation of a map with a one milliGal contour interval (Fig. 4). The gravity values exhibit an increase towards the west and southwest, with the lowest values (-69 mGal) located in the northeast corner and the highest values (-35 mGal) in the west. The calculated horizontal gradient is 0.9 mGal/km from east to west and about 1.1 mGal/km from northeast to southwest.

Linear anomalies are predominantly interpreted as faults. Comparison of gravity anomaly highs with the geological map (Fig. 3) suggests an association with anticlines, while gravity lows correspond to synclines and plain areas. Ghaib and Salaee (2021) gave a comprehensive qualitative description and interpretation of those Bouguer anomalies.

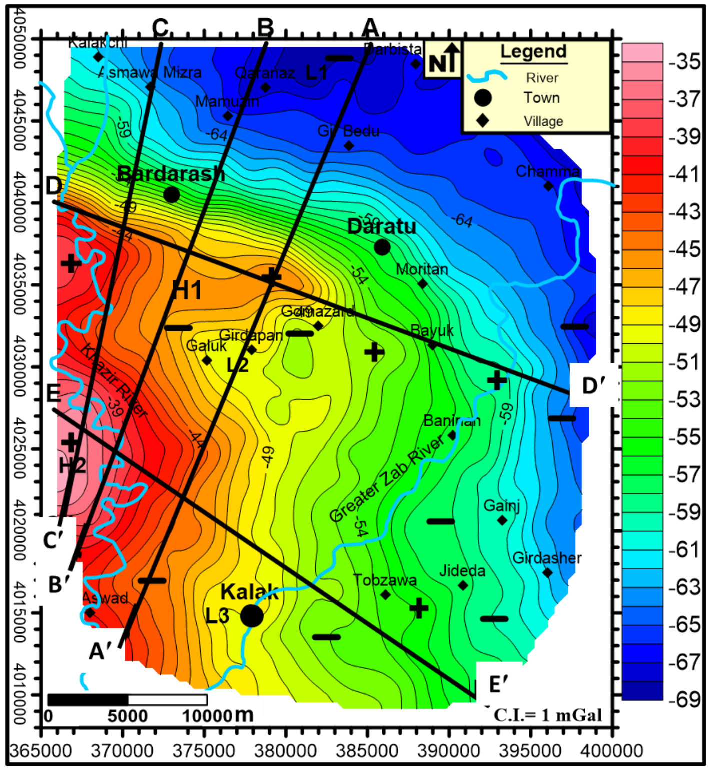

Figure 4: Bouguer anomaly map of the study area showing the location of interpreted profiles (Salaee, 2015).

4.2 Rock Densities

The accurate determination of rock unit density is significant in the correction and interpretation of gravity anomalies, particularly when employing modeling techniques. It is crucial to ascertain these density values as precisely as possible. In pursuit of suitable and reliable density contrast values, a thorough review of existing literature has been undertaken, as shown in table 2. This comprehensive survey of relevant sources ensures that the density information utilized in the correction and interpretation processes is grounded in a robust and well-informed foundation. The thorough review of literature

(Ditmar and Team, 1971, Al-Shaikh et al., 1975, Ahmed M., 1980, Ahmad T., 1980, Ghaib, 2001, Al-Dawoody, 2004) resulted in the compilation of the densities listed in Table 2. The averages were calculated, and suitable densities for the three groups of rocks were determined. Hence, the density contrast between these groups is 0.2 gm/cm3. Notably, the oil wells within the study area did not contribute to this effort due to the lack of available density data. This absence of density information from the oil wells highlights the challenges in obtaining comprehensive and diverse datasets, which are crucial for accurate gravity anomaly corrections and interpretations in the geological context of the study.

Table 2: Mean density of various rock formations in the vicinity of the study are

Author / Rock Unit	Ditmar et. al., (1971)	Al-Shaikh et. al., (1975)	Ahmed, T. (1980)	Ahmed, M. (1980)	Ghaib (2001) Erbil	Ghaib (2001) Aqra	Al-Dawoody A. N. (2004)	Average	Group average as used by the Present authors
Surface Soil	--	2.0	--	--	1.7	--	--	1.85	Neogene 2.23
Upper Bakhtiari Fm.	2.32	--	2.41	2.42	2.41	--	--	2.39	
Lower Bakhtiari Fm.	2.32	--	2.18	2.16	2.19	2.31	--	2.23	
Upper Fars Fm.	2.32	2.25	2.00	2.08	2.23	2.34	2.25	2.21	
Lower Fars Fm.	2.33	2.45	2.26	2.3	2.33	2.27	2.28	2.32	
PilaSpi Fm.	2.44	2.5	2.44	2.47	2.41	2.45	2.55	2.47	Paleogene 2.43
Gereus Fm.	2.44	2.3		2.17	2.38	1.93	2.23	2.24	
Kolosh Fm.	2.44	2.3	--	--	2.43	2.47	2.41	2.41	
Cretaceous rocks	>2.44	2.6	--	--	2.66	2.57	2.62	2.61	Cretaceous 2.63

4.3 The Process of Modelling

Gravity modeling typically constitutes the concluding phase in gravity interpretation, aiming to deduce the density, depth, and configuration of one or more subsurface bodies based on the measured gravity anomalies. The modeling process commonly employs a residual gravity anomaly, necessitating the interpreter to account for the density contrast between the targeted body or group of bodies and the surrounding materials. The goal of the modeling procedure is to translate the geophysical designed model into geological terms, facilitating the estimation of subsurface geological features and the demarcation of boundaries between distinct rock types that yield optimal density contrast. The modeling results' precision depends on the volume and quality of information gathered by the interpreter throughout the process.

Based on the geological successions given by two boreholes present within the area of study (Ghaib and Salaee, 2021) and the surface geology of the study area and surroundings, different rock formations are classified as three age-based groups of rock formations, namely: Neogene, Paleogene, and Cretaceous.

Certain geological structures can be approximated to models with known geometrical shapes. Some of the examples are a buried cavity may be represented by a sphere, a salt dome by a vertical cylinder and a basic igneous dyke by an inclined sheet or prism (Reynolds, 2011)).

A noteworthy conclusion from (Litinsky, 1989) asserts that the gravity anomaly observed above a layered sedimentary basin closely aligns with the anomaly calculated over a basin of identical configuration and depth but filled with homogeneous (unlayered) sediments, having a density equivalent to the actual layered basin.

This implies that there is no imperative need to separately consider the effects of individual layers. Particularly in relatively thick successions, the density contrast tends to approach a minimal value as depth increases.

The modelling process was performed using (Oasis Montaj) program by matching the calculated gravity values and the observed gravity values for a certain profile. The amount of error is minimized to lowest value as much as possible to produce the best matching between the observed and calculated data. Prior information about the area's geology is important and should not be forgotten in the modeling to make results more reliable, realistic, and consistent with the area's general geology.

5. Results

Anomalies on a Bouguer map reflect both deep and shallow causative bodies. In each interpreted profile, these are presented as Regional and Residual components. This study involved interpreting models to understand deep and shallow structures. The regional anomaly profiles were used to model the basement complex for deep-seated structures, while the residual anomalies were modeled for shallow structures within the sedimentary cover. The calculated gravity values for the suggested models are shown in figures 5-10, the solid line in each figure is the calculated anomaly due to the model, while the dotted line is the Bouguer anomaly along the profile.

5.1 Deep Seated Structures

Three of the five profiles were selected to model the basement rocks. The first profile, AA′ trends in NNE-SSW, while DD′ and EE′ trend in the NW-SE directions. The density contrast between basement rocks and sedimentary rocks of (0.18 gm/cm3) was used for the modeling; this density contrast was presented by Ghaib (2001) in Erbil plain some 30 km to the east, for the same purpose. In all the modelling figures, the Bouguer Anomaly map is put beside the model to show the profiles location for more clarity without going back each time.

5.1.1 Profile AA′ (Fig. 5)

The minimum gravity value along this profile is approximately -68 mGal in the NNE part, while the maximum gravity value is about -41 mGal in the SSW part. The profile is trending in the NNE-SSW direction across the Bardarash Anticline and extends for approximately 40km. The suggested model shows that the interface between the basement rocks and sedimentary cover is sloping towards NNE in such a way that its depth is about 5 km in the SSW and about 9 km in the NNE part. It has a gradient of about 110 m/km towards the NNE direction.

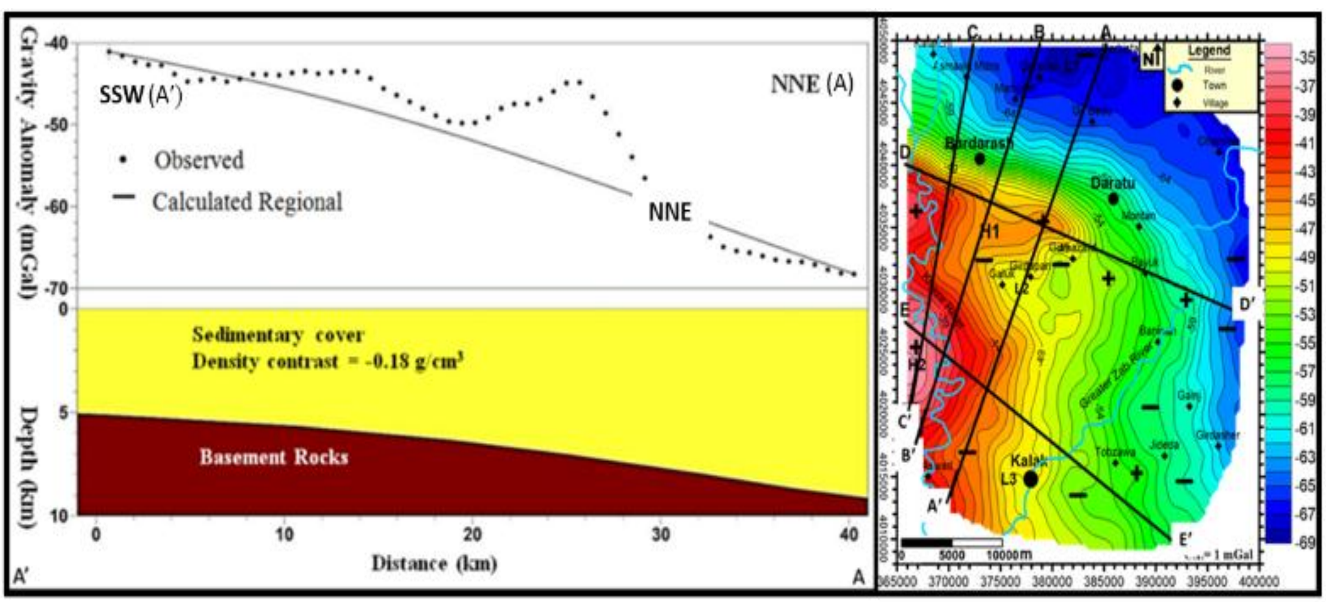

Figure 5: Profile AA′

5.1.2 Profile DD′ (Fig. 6)

This profile extends for about 34 km from the northern limb of the Bardarash Anticline to the eastern part of the study area. The suggested model of this profile shows the presence of a fault along the Greater Zab River. The model is designed so that it extends towards southeast to join the adjacent Bouguer anomaly map of Erbil Plain executed by Ghaib (2001). It shows a Graben structure with a throw of approximately 200 m. The presence of a fault beneath the Greater Zab River possibly means that this River is affected by this fault and following its strike. This conclusion was tectonically suggested by Numan (1984) and by Ghaib and Aldawoodi (2009) through geophysical surveys. The maximum and minimum gravity values are about -44 mGal and -72 mGal respectively.

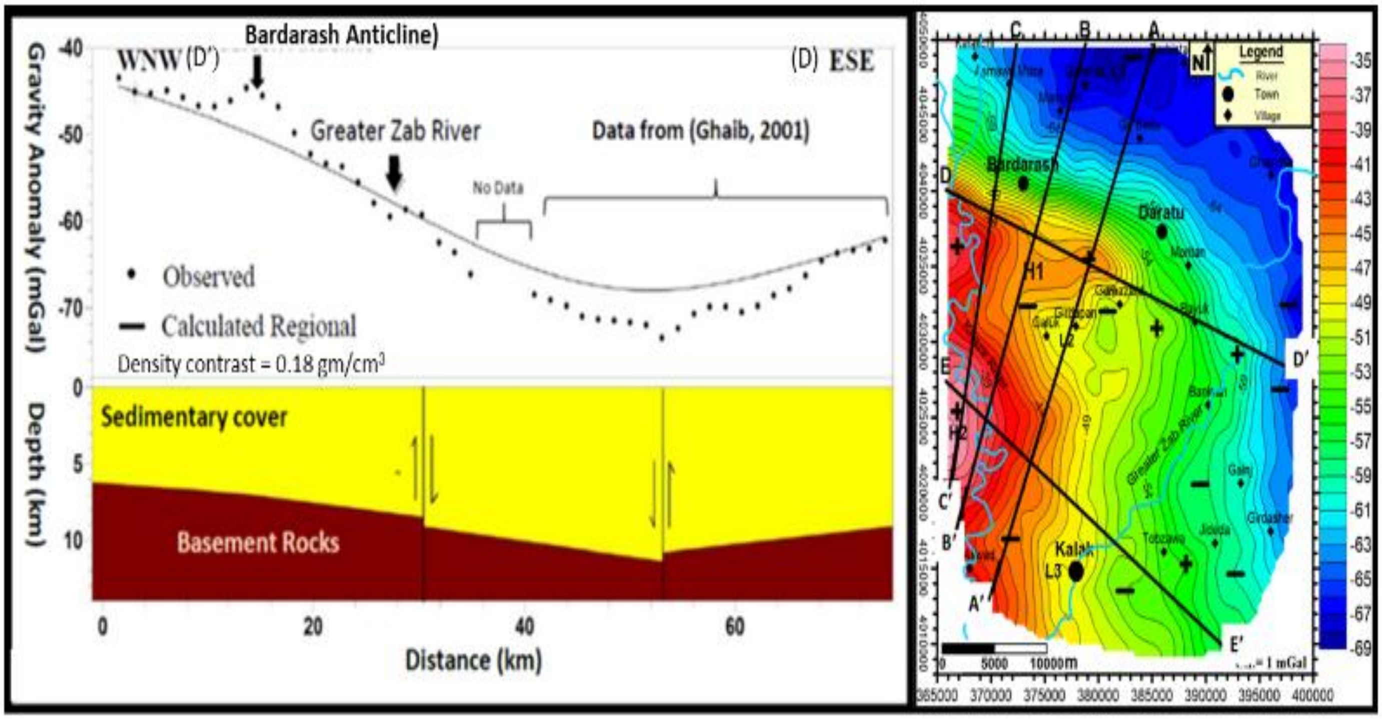

Figure 6: Profile DD′

5.1.2 Profile EE′ (Fig. 7)

The profile (EE′) covers about 31 km from the northern part of Ain Al-Safra Anticline to the southeastern part of the study area. It crosses the Zab River between Kalak Town and Tobzawa village. The maximum gravity value is about -36 mGal in the northern part of Ain Al-Safra Anticline, while the minimum gravity value is approximately-57 mGal in the southeastern part of the study area. This profile coincides with the calculated regional trend in most parts except over the Ain Al-Safra Anticline where it has a positive gravity value. The model section is influenced by two faults, one beneath the Zab River while the other is in the eastern plunge of the Ain Al-Safra Anticline.

In both DD′ and EE′ (Figs. 6 and 7), the two aforementioned faults affect the basement up to the sedimentary cover. One of these faults trends in NE-SW direction along the Greater Zab River and has a throw value of about (600 m) while the other trends N-S along the Khazir River have the same throw value. In a separate gravity survey along a traverse across the Zab River, Ghaib and Al-Dawoody (2010) calculated a throw of 400 m for a fault parallel to the river.

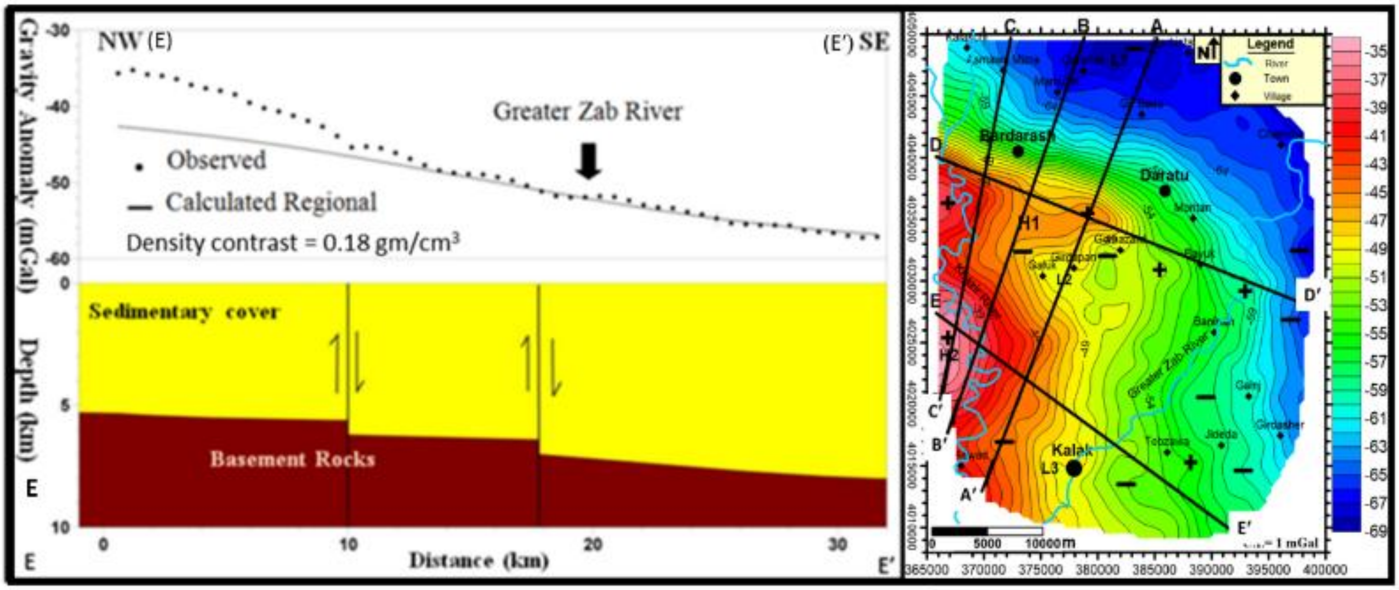

Figure 7: Profile EE′

5.2 Shallow Seated Structures

For the aim of interpretation of shallow structures, the five profiles were used. The regionals of these profiles were removed and used for the basement modeling in the previous sections. The remaining residuals are used in this section.

As mentioned before, the sedimentary rock formations are divided into three groups according to their density and age. The mean density of each group is calculated. Density contrast between groups is calculated to be 0.2 gm/cm3 (Table 2).

5.2.1 Profiles AA′, BB′ AND CC′ (Fig. 8)

These three profiles extend for 30, 35 and 40 km respectively and are almost parallel to each other in the NNE-SSW direction. They cut obliquely the Bardarash Anticline which extends in the W-NW direction and reaching the southwestern plunge of Ain-Alsafra Anticline. All profiles showed two positive and two negative anomalies. The center of the positive anomalies is situated above the two present anticlines. These anomalies have amplitudes ranging from 7 to 10 mGal over the Bardarash Anticline and 4 to 6 mGal over the Ain-Alsafra Anticline.

The best possible geological solution for the subsurface features of the three profiles regarding the positive anomalies, is illustrated in figure 8. Two reverse faults are suggested, cutting both (Palogen-Neogen) and (Neogen-Cretaceous) rocks units. These two reverse faults cut both northern and southern limbs of Baradarash Anticline generating a Horst structure with a throw value of about 200 m on both sides. The fault of the southern limb of Bardarash Anticline might be generated due to the movement of rock units on the Alan Halite Formation (Early Jurassic age) that acts as a detachment surface. Also, it is noticed that the width of the Bardarash Anticline is widening towards northwest, as indicated by the increasing distance between the faults on both limbs of the anticline and half width of the anomaly. These faults are trending WNW-ESE along the Bardarash Anticline’s limbs with a SW and NE dip direction.

The foreland area of Bardarash Anticline is shown up gravimetrically as low values reflecting an open area (Mamuzin plain) with undulated syncline in the subsurface (i.e., northeastern end of the profiles-Fig. 8). Most of the Iraqi wide synclines have this subsurface undulating feature (Ghaib, 2001).

The effect of the Ain-Alsafra southeastern plunge is shown as a gentler positive anomaly ranging in amplitude between 4 and 6 mGal in the three profiles. A simple geological situation is suggested in the interpretation of this anomaly.

The low gravity anomaly that is located between

Bardarash and Ain Al-Safra anticline is the reflection of the Galuk Syncline with slight dips on both limbs. The other low gravity anomaly in the northern part of the profile is related to the Mamuzin plain. The Kalak plain has low gravity values with simpler geological picture that is in the southwest of the profile AA′.

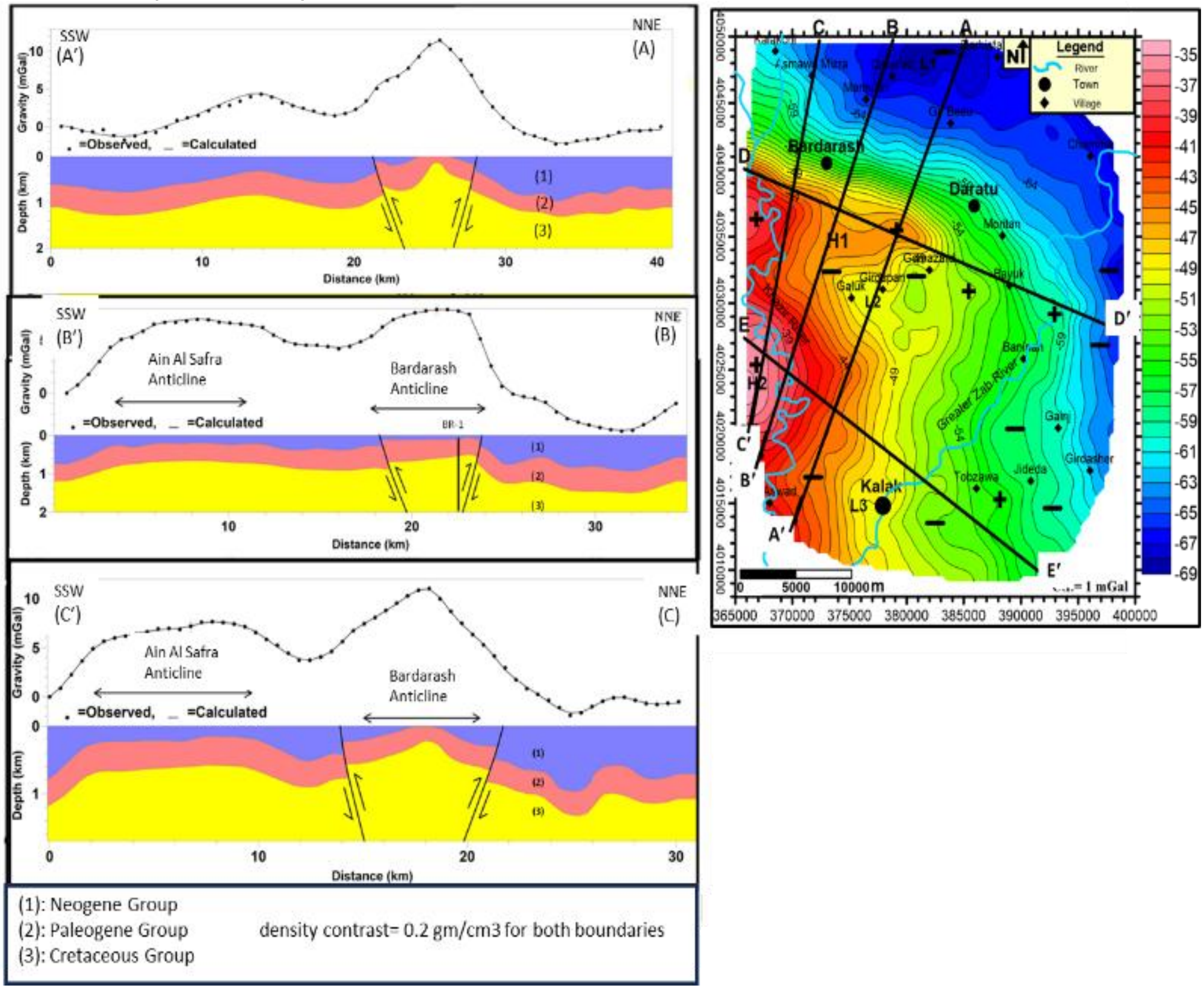

Figure 8: Profiles AA′, BB′ and CC′

5.2.2 Profiles DD′ (Fig. 9)

This profile crosses the Greater Zab River at the eastern part of the study area. The first part of the anomaly is in the northern limb of the Bardarash Anticline and the highest positive anomaly is in the middle part of the profile with a magnitude of approximately 6 mGal. The plunge of Bardarash anticline is in the middle part of an anomaly few kilometers to the west of the Bayuk village.

From the eastern part of Bayuk village and southeast of the Zab River, the rapid decrease in gravity values is interpreted as a fault that extends from the basement up to the sedimentary cover; the throw value of this fault is approximately 200 m.

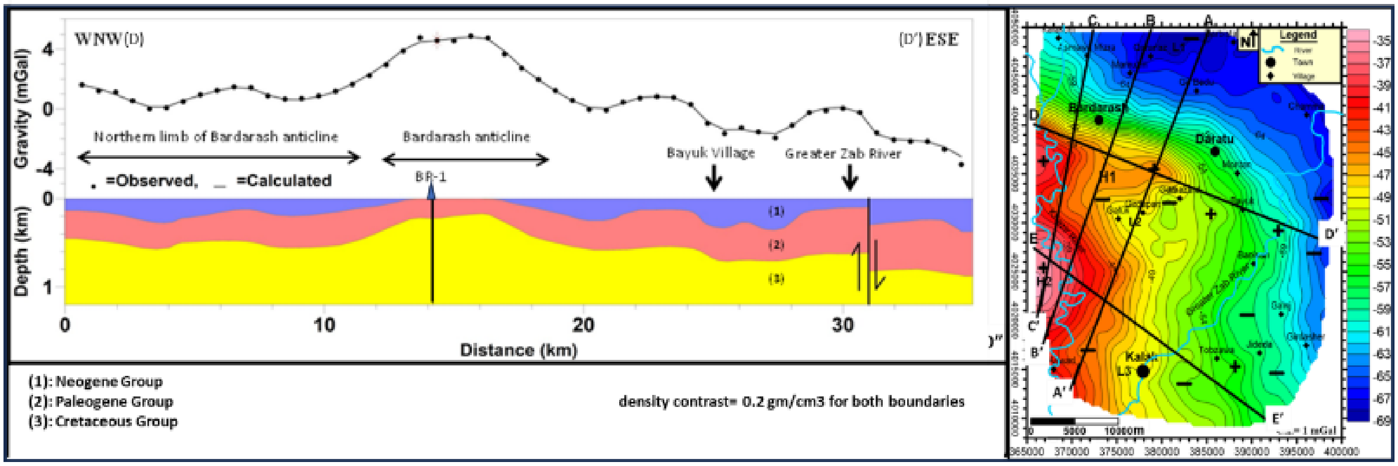

Figure 9: Profile DD′

5.2.3 Profiles EE′ (Fig. 10)

It also crosses the Greater Zab River between Kalak Town and Tobzawa District. The gravity anomaly is interpreted as a fault between the Kalak Town and Tobzawa Village that extends from the sedimentary cover down to the basement rocks. The northwestern part of the profile (northern limb of Ain Al-Safra Anticline) is also affected by a fault with a throw value of about 200 m trending in the N-S direction.

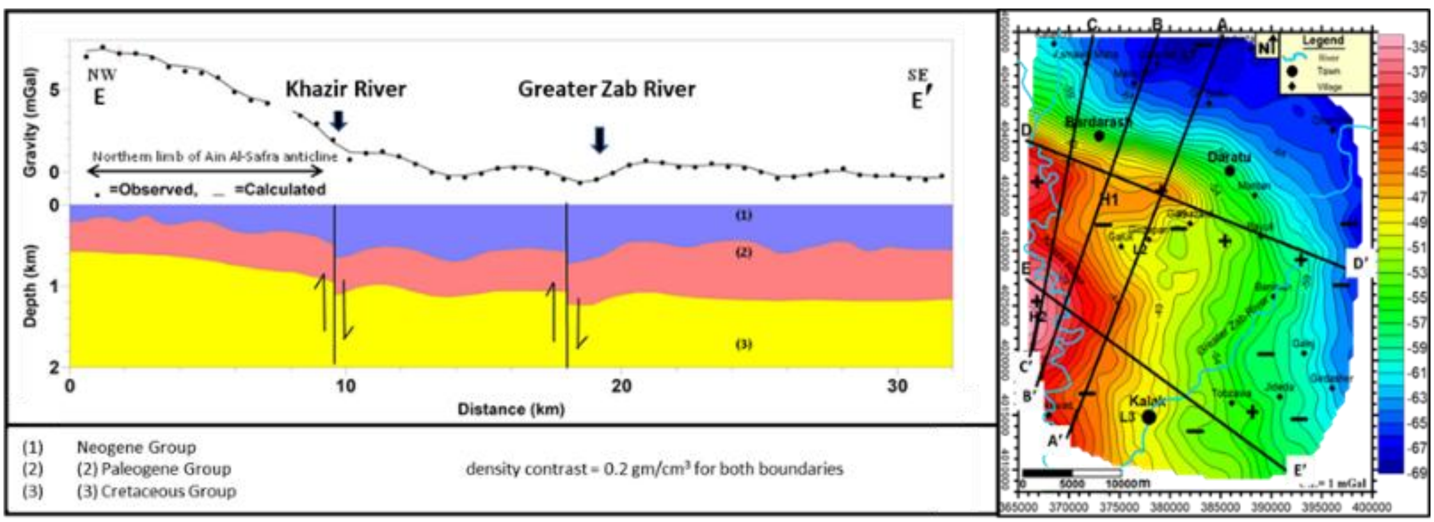

Figure 10: Profile EE′.

6. Conclusions

Based on the results of the study, the following points can be concluded:

- For deeper-seated structures (i.e., basement rocks), three of the five profiles in the NNE-SSW, WNW-ESE and NW-SE directions were analyzed. A density contrast of 0.8 gm/cm³ between the sedimentary cover and basement rocks was used for modeling. It was found that the basement rocks' surface slopes towards the NNE at a gradient of 110 m/km, with depth ranging from 5 km on the SSW end to 9 km on the NNE end of the profile.
- Profiles cutting both the Zab River and the Bardarash Anticline in WNW-ESE and NW-SE directions revealed two important faults in the form of graben and step, nearly parallel to the Zab River's course, one of them located directly on the river.
- For the sedimentary cover (considered as shallow structures), all five profiles were utilized. The models were categorized into three groups of rock formations: Neogene,

Paleogene, and Cretaceous. Three profiles trending in the NNE-SSW direction crossed the Bardarash Anticline, extending to the southwestern plunge of Ain-Alsafara Anticline in the northeast, one of them crossing the Khazer River in the southwest. A density contrast of 0.2 gm/cm³ was used for modeling. The suggested models indicated that the Bardarash Anticline is affected by two faults on both limbs, forming a horst that widens towards the northwest. Both faults have a throw value of approximately 200 meters. It is believed that the fault on the southern limb of the Bardarash Anticline extends down to the basement rocks, parallel to the Khazer River's flow direction.

- Two profiles extending in the NW-SE direction showed the presence of two faults, one trending NE-SW along the Greater Zab River and the other in a N-S direction along the Khazir River. These faults have a throw value of about 600 meters and extend deep into the basement rock.

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