Qualitative Interpretation of Gravity Data Collected in Kalak-Bardarash Area-NW of Erbil City, Iraqi Kurdistan Region

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Abstract: A total of 610 gravity stations were taken to cover the area around Kalak and Bardarash Towns northwest of Erbil City. The existed net of roads was followed to collect the data. All necessary corrections were carried out to calculate and display the complete Bouguer anomalies. The Bouguer anomaly map was carefully analyzed. Regional and residual maps were also derived and displayed using different techniques.

The visual inspection of the Bouguer anomaly map showed the presence of five major anomalies: two positive and three negative. Among them is the important high south of Bardarash Town which is the main oil field structure in the area. When these anomalies were compared with the surface geology, lineaments on Landsat and Aster images a good and reliable consistency was found with slight shift in the surface anticlinal axis of Bardarash with that obtained from gravity. The analysis of the regional anomaly map shows that all the anomalies revealed by the Bouguer and residual maps are super-imposed on a main regional anomaly almost trending towards northeast. This major anomaly, which is considered to reflect the effect of basement rocks, shows that the basement complex surface is inclined toward the northeast and East. It has a depth ranging between 6 and 9 km. with the presence of many faults some of which are continuing upwards to the surface.

Keywords: Kalak, Bardarash, Iraq, Bouguer Anomaly

1. Introduction and Location

Applied geophysics involves the study of the hidden parts of the Earth, by measuring their physical properties with appropriate instruments above the surface. It also includes interpretation of the measurements to obtain useful information on the structure and composition of the concealed zones. One of the oldest branches of applied geophysics is the gravity prospecting by which we measure the variations in the pull of gravity from rocks within the upper few kilometers of the Earth’s crust. Different rock types have different densities, and the denser rocks have the greater gravitational attraction. If the higher density formations are arched upward in a structural high, such as an anticline, the earth’s gravitational field will be greater over the axis of the structure than along its flanks (Dobrin & Savit, 1988). The primary aim of any geophysical survey is to determine the subsurface geology in terms of its lithology, stratigraphy and structure.

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The study area is in the North West of Erbil city in north of Iraq (Iraqi Kurdistan Region). The gravity stations of the study area were taken around the Greater Zab River in Kalak, Khazir River in Khazir and Bardarash Mountain in Bardarash. The location is defined by zone 38; Northing: (4008700 – 4049900) and Easting: (365550 – 399400), it covers approximately 1400 Km^2 (Figs. 1 and 2).

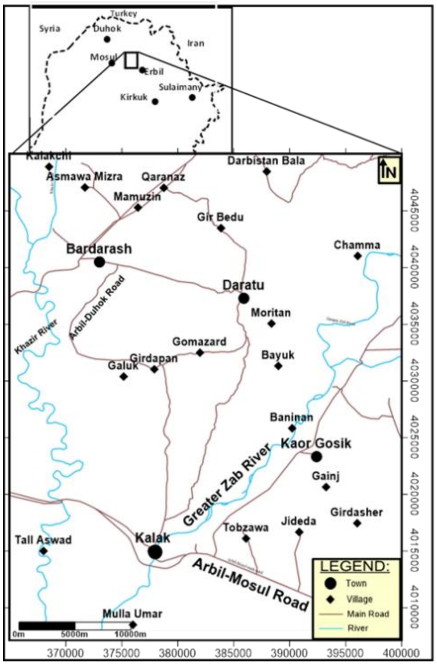

Figure 1: Location map

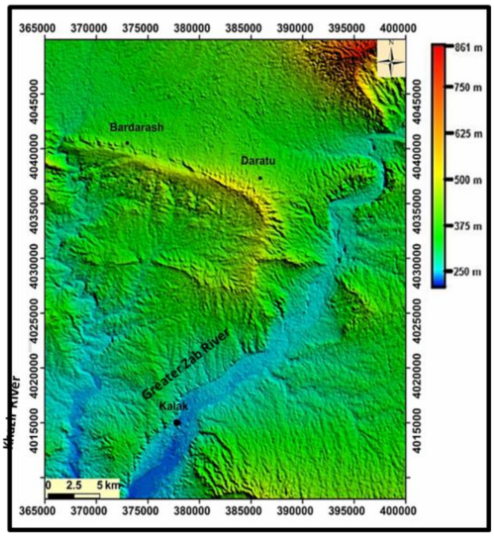

Figure 2: (DEM) image map

2. General Geologic Setting

The study area is part of the Foreland folds in northern and northeastern Iraq; it is situated on both Mosul and Kirkuk basement blocks on both sides of the Greater Zab River, within the Foothill Zone (Numan (1984) and Jassim and Goff (2006). The folds on the Mosul block mostly trends E-W as Taurus direction and on Kirkuk block trends NW-SE with the main Zagros trend. The Mosul block on the western side of the Greater Zab River is elevated (1.5-3.0 Km) with respect to Kirkuk block on the eastern side of the river (Ghaib, 2001).

The Zagros Orogenic belt of Iraq can be divided into the Zagros Structure, Imbricated Zone, Highly Folded Zone, Foothill Zone and Mesopotamian Foreland Zone (Jassim $ Goff 2006) (Fig. 4). Accordingly, the area is located within the Foothill Zone which was studied (among other Zones) in details for oil potentialities during the last decades.

Geologically the study area is mainly covered by river terraces, which are composed of conglomerate, siltstone, sandstone, rock fragments, silty and clayey soil (Sissakian, 1997), (Fig. 5). Followings are brief lithological descriptions of the formations which are cropping out in and around the study area (Jassim & Goff, 2006, Buday 1980, Omer, 2005):

- PilaSpi Formation (Middle-Upper Eocene): This formation crops out only in the western part of the study area. It is mainly composed of crystalline dolomite and calcareous dolomite with minor amounts of clayey limestone.

- Lower Fars (Fat'ha) Formation (Middle Miocene): It is composed of anhydrite, gypsum and salt, inter-bedded with limestone, marl, and relatively fine grained clastics. In Damir Dagh-2 well (few kilometers to the south of Kalak town) the formation consists mainly of clastic sedimentary rocks with anhydrite and gypsum.
- Upper Fars (Injana) Formation (Upper Miocene): It consists of cyclic deposits of clastics, which in general coarsen upwards. Each depositional cycle consists of mudstone and sandstone. The mudstone is occasionally silty with some thin horizons of inter-bedded siltstone, which are reddish brown, and brown in color.
- Lower Bakhtiari (Muqdadiya) Formation (Pliocene): The formation consists of cyclic deposits of clastic materials getting finer upwards. The cycle starts by claystone, pebbly sandstone and thick layers of conglomerate. In the Damir Dagh well-2, it consists of inter-bedded grainstone and sandstone, silty and sandy claystone with calcite and anhydrite minerals in some parts.
- Upper Bakhtiari (Bi Hassan) Formation (Pliocene): It consists of molasses sediments represented by deposition of conglomerates and claystone with some sandstone and siltstone beds.

Information of the subsurface geology is estimated from lithologic columns of two deep oil wells which are present in the area and kindly provided by (Ministry of Natural Resources – KGR). Table shows the thickness and age of rock units in these two wells.

3. Theoretical Background

The gravity method in geophysics is employed to determine the effect of subsurface density distribution by measuring the variation of the earth's gravity field. Measurements of gravity field are usually made on the earth or ocean surface. The scale of investigations depends on the type of geological problems. It varies from few microGals to one milliGal of measurement accuracy, which is

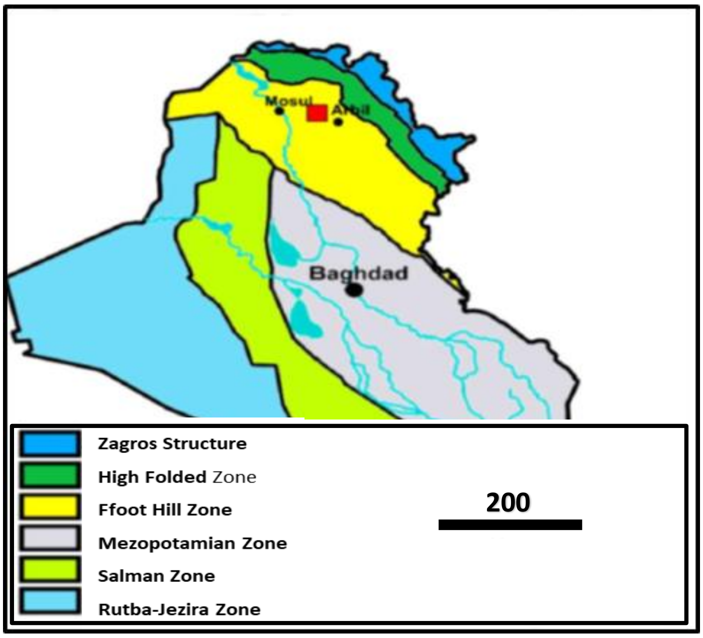

Figure 4: Tectonic map of Iraq (Jassim & Goff, 2006)

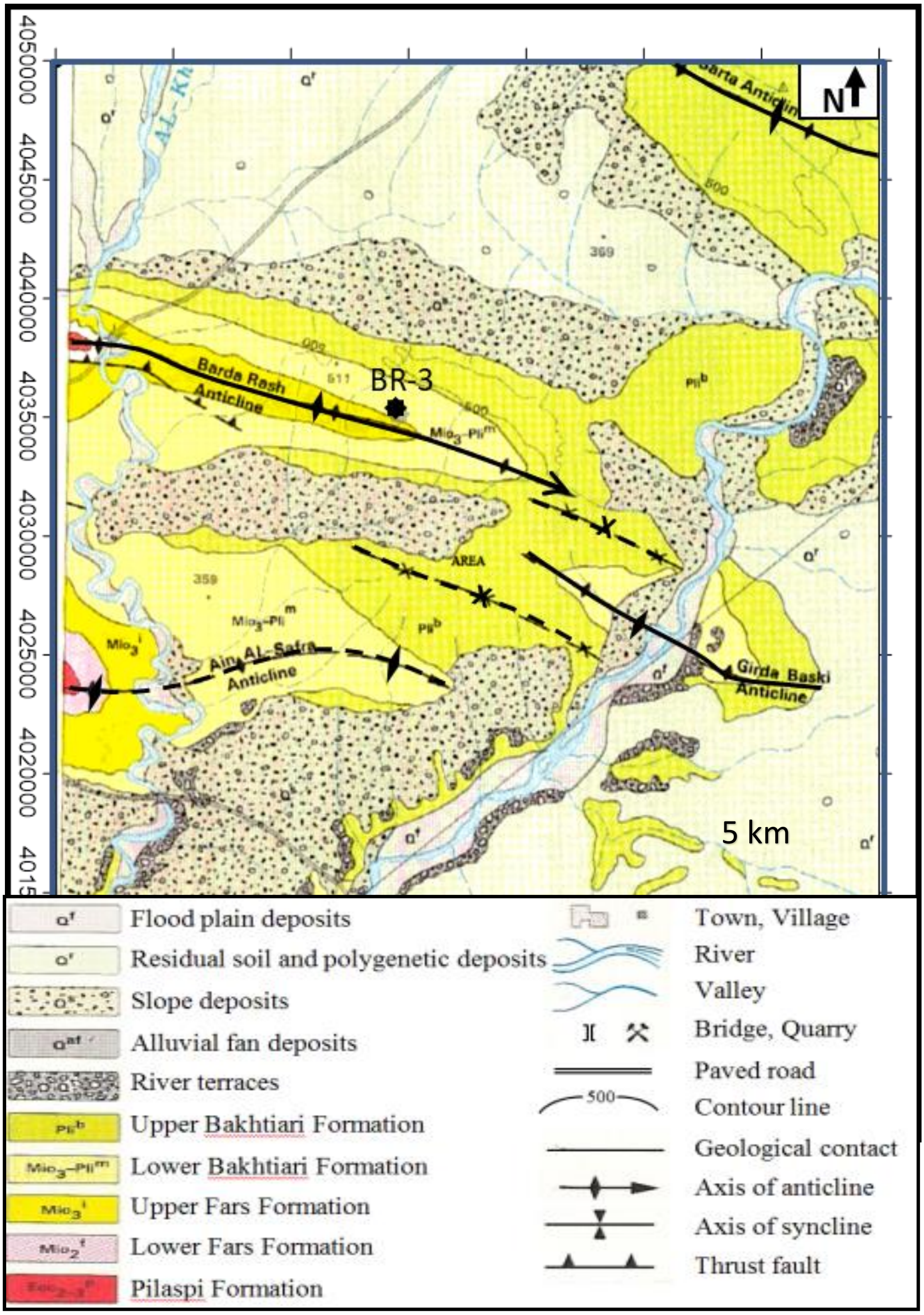

Figure 5: Geological map of the area (Sissakian, 1997)

a few millions of average earth's gravity field (9.8 m/s2) and station intervals of a few meters to a few kilometers (i.e. regional gravity surveys, reconnaissance gravity surveys and detailed gravity surveys), (Gupta, 2011).

Table 1: Geological column of existed rock formations in Damirdagh well-2

Formations	Depth to top of the formation (m)	Thickness (m)	Age	Groups
Lower Bakhtiari	51	226	Tertiary	Neogen
Upper Fars	277	434	Tertiary	
Lower Fars	711	283	Tertiary	
Pila Spi	994	143	Tertiary	Paleogen
Gercus	1137	53	Tertiary	
Sinjar	1190	115	Tertiary	
Kolosh	1305	333	Tertiary	
Shiranish	1638	128	Cretaceous	Mesozoic
Gulneri	1766	1	Cretaceous	
Qamchuqa	1767	141	Cretaceous	
Sarmord	1908	199	Cretaceous	
Garagu	2107	116	Cretaceous	
Najmah	2223	730	Jurassic	
NaoKelekan	2953	39	Jurassic	
Sargelu	2992	34	Jurassic	
Alan	3026	56	Jurassic	
Alan Halite	3082	180	Jurassic	
Lower Alan Anhydrite	3262	40	Jurassic	
Mus	3302	20	Jurassic	
Adayah	3322	166	Jurassic	
Butmah	3488	223	Jurassic	
Baluti	3711	57	Triassic	
Kurra Chine	3768	252	Triassic	
Total depth	4020			

Table 2: Geological column of existed rock formations in Damirdagh well-2

Formations	Depth to top of the formation (m)	Thickness (m)	Age	Groups
Lower Fars	25	230	Tertiary	Neogen
Pila Spi	255	188	Tertiary	Paleogen
Gercus	443	26	Tertiary	
Sinjar	469	116	Tertiary	
Kolosh	585	250	Tertiary	
Shiranish	835	50	Cretaceous	Mesozoic
Bekhme	885	43	Cretaceous	
Kometan	928	52	Cretaceous	
Qamchuqa	980	88	Cretaceous	
U. Sarmord	1068	37	Cretaceous	
L. Qamchuqa	1105	27	Cretaceous	
M. Sarmord	1132	164	Cretaceous	
Garagu	1296	56	Cretaceous	
Najmah	1352	616	Jurassic	
Sargelu	1968	332	Jurassic	
Alan	2300	652	Jurassic	
Mus	2952	41	Jurassic	
Adayah	2993	218	Jurassic	
Total depth	3211			

Although gravity at the Earth's surface is nearly constant, it is slightly greater where dense rock formations lie close to the surface. Gravitational force, therefore, increases over the tops of anticlinal folds and decreases over the top of salt domes. Very small differences in gravitational force can be measured by a sensitive instrument known as the gravimeter (Reynolds, 1997).

The basis of the gravity survey is dependent upon the first and second Newton's laws of attraction.

$$F = G\frac{m_1 m_2}{r^2} \text{ and } F = mg$$

Where (F) is the force, (m1) is the mass of the first body, (m2) is the mass of the second body, (r) is the distance between the centers of the two masses, (G) is the gravitational constant which is equal to 6.67x10-11 N m2 Kg-2 and (g) is the gravity which is measured in the field. The combination of the above two equations give:

$$F = \frac{GM}{R^2} m = mg, \text{ thus } g = \frac{GM}{R^2}$$

Where (M) is the mass of the Earth while (R) is its radius.

Thus, the value of gravity (g) at any location on the earth is directly proportional to the mass of the Earth and inversely proportional to the square of the radius. The value of gravity varies due to variation of subsurface geology and structures. The density of the rocks is important in gravity survey because there is a force of attraction between the gravimeter and the mass of rocks, therefore gravity varies with variation in density. High density rocks have high gravity anomaly while low density rocks have low gravity anomaly.

Before the results of gravity survey can be interpreted in geological terms, raw field gravity data have to be corrected to a common datum such as sea level (geoid) or relative to a local base station. All effects other than those come from sub-datum structures should be removed, this process is known as gravity data reduction which leads to a final gravity value reflecting the effect of the subsurface and called Bouguer Anomaly. (Reynolds, 1997).

4. Data Collection and Reductions

The standard formula for the calculation of simple gravity anomalies assumes a flat earth surface at the observation point. Gravity stations should be sited on a flat area with at least 200m clearance from sharp changes in ground elevation. Moreover, surveys designated to solve geological problems should contain profiles of variable station spacing (Murray and Tracey, 2001). These two concepts were taken in mind to collect three types of data, gravity values at previously chosen locations, gravity values for base stations and the coordinates of the measurement points. LaCoste and Romberg gravimeter-model G and Garmin 60CSx-GPS were used to collect gravity measurements and geographic coordinates respectively.

For repeated readings Erbil primary base station (cited in Ghaib, 2001) was transported to three local stations inside the study area. These stations are shown in figure 6 and their information is given in table 2.

Field data were collected by two steps, the first was surveying 189 points to view a generalized Bouguer map (large stars in figure 7). In the second step 421 stations were added (small stars in figure 7) to reach a total number of 610 with an inter-distance between successive stations of 800-1000 meters.

Density values of the rock units are important for both corrections and interpretation. Many literatures were studied to obtain suitable and confidential values. Unfortunately, the oil well which is present in the area does not include density data. Table 3 summarizes those literatures which were depended upon for both corrections and interpretations.

5. Data Processing

After completing the field work, all data were corrected relative to the Erbil primary base station to produce the Bouguer anomalies. Drift, Latitude, Free Air, Bouguer and Terrain corrections were carried out. The latter one is difficult to be done manually according to hammer chart or even using simple programs, and requires a lot of time, as well as facing errors.

Table 3: Coordinates and gravity values of base stations

	Erbil Primary BS.	Kalak BS.	Tobzawa BS.	Bardarash BS.
Latitude	36° 11' 15.37"N	36° 15' 36.54"N	36° 15' 19.71"N	36° 29' 46.37"N
Longitude	43° 59' 35.23"E	43° 39' 24.84"E	43° 44' 27.73"E	43° 35' 58.08"E
Elevation	396	257	359	397
Absolute gravity value (mGal)	979679.434	979734.47	979708.41	979720.49
Theoretical gravity value (mGal)	979834.58	979854.93	979841.52	979862.32

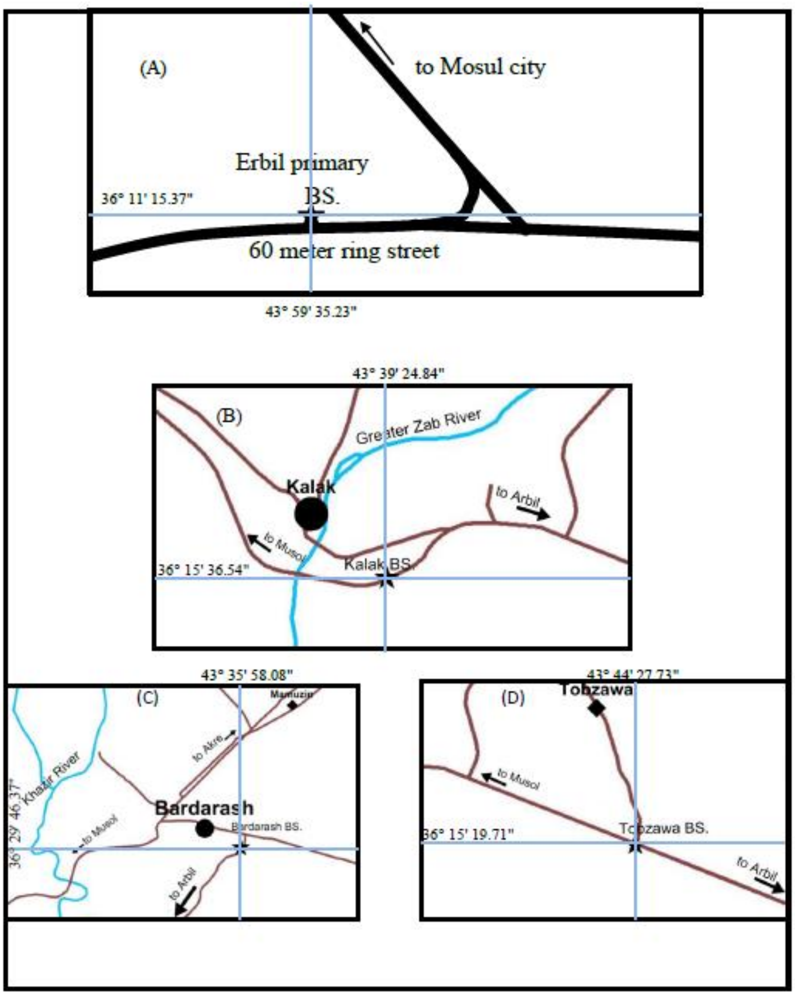

Figure 6: (A) Erbil Primary Base Station, (B) Kalak Base Station, (C) Bardarash Base Station and (D) Tobzawa Base Station

Ali (2010) applied a combination of (AutoCAD and MapInfo) software to do that digitally. On the other hand, Al-Majid (2013) carried out Terrain correction using (Geosoft Oasis Montaj software) which was used in this study to calculate the terrain correction using Digital Terrain Modeling (DTM) image of 30m sample spacing that is free and can be downloaded from the internet by some programs such as (Global mapper). (Salaee, 2015).

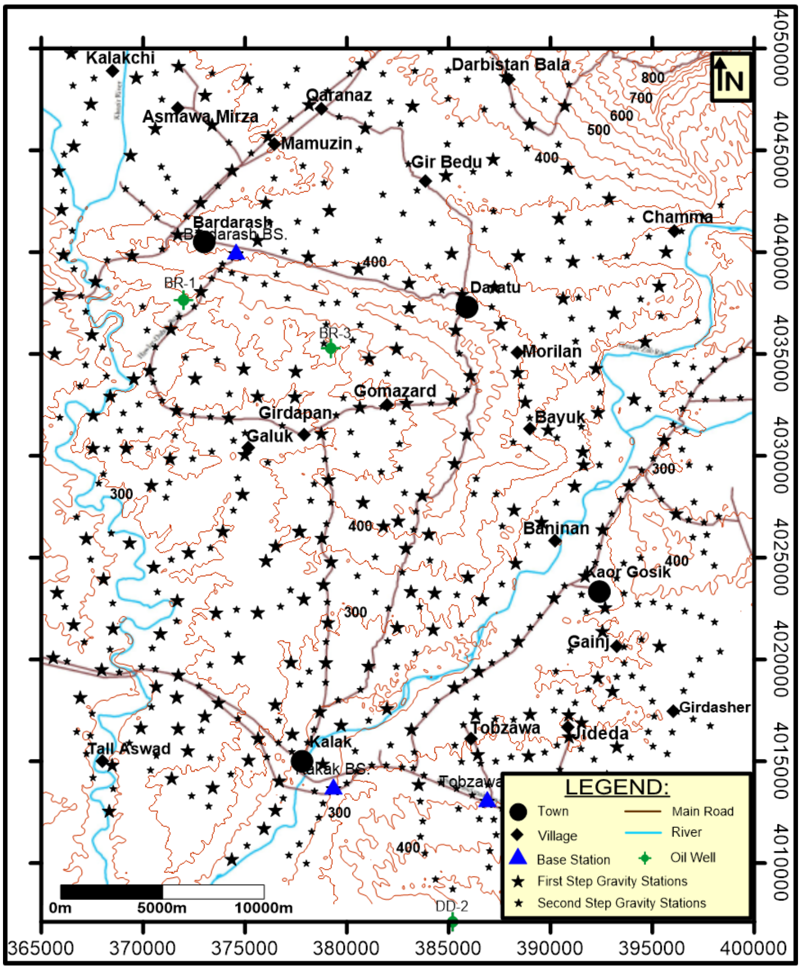

Figure 7: Location of gravity stations

6. Results and Discussions

6.1 Bouguer Anomaly Map

After carrying out all necessary corrections the total errors arising from the corrections were found to be (0.01mGal). The final Bouguer anomaly map is shown in figure 8.

A rapid inspection of the map shows that gravity values decrease from west and southwest towards east, northeast, and north. The lowest gravity values are shown in the northeast reaching -69 mGal, while the highest values are present in the west reaching -35 mGal. The horizontal gradient from west to east is about 0.9 mGal/km and from southwest to northeast is about 1.1 mGal/Km.

Table 4: The average densities of different rock formations

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	Present author
Surface Soil	--	2.0	--	--	1.7	--	--	1.85	2.22
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	2.42
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	2.62

The gravity anomaly highs, when compared with the geological map (Figure 5), appear to be related to anticlines while gravity lows related to synclines and plain areas. There are some major anomalous features in the area; they are:

- Bardarash High (H1): It is in the northwestern part of the study area and elongates westward out the scope of the area. Its maximum gravity value is about (-39 mGal) with a relief of about (15 mGal). This two-dimensional anomaly trends approximately E-W that coincides with the main trends of the Taurus tectonic orientation. It is bounded from the north, northeast and east by linear anomalies. They are trending WNW-ESE in the north, swinging to NW-SE in the northeast and east, and extending overall for about (30 Km). The linear contour lines have a steep gradient of about (4 mGal/Km), decreasing to about (2 mGal/Km) in the east. Contour lines in the northwestern part of these linear anomalies are distorted, which may be due to shallow structural variations affecting the strata.
- Ain Al-Safra (Zardik) High (H2): This anomaly is situated in the western part of the study area extending towards west out the scope of the map. The maximum gravity value in this sector is about (-35 mGal) with a relief of about (4 mGal). It is bounded by two sets of contours, one set from northeast trending NW-SE with a horizontal gradient of about (1.5 mGal/Km), another set from southeast trending NE-SW with approximately same horizontal gradient.
- Mamuzin Low (L1): It is in the northern part of the study area with a minimum gravity value of about (-68mGal). It is bordered from south by wavy contour lines extending from west to the south of this sector till the Chammah Village in the northeast part of the study area. This anomaly extends to the north outside the scope of the map.
- Galuk Low (L2): It is extending from the center to the western part of the study area with a minimum gravity value of about (-50mGal) and a relief of less than (1mGal). It is bounded from southwest by a linear contour anomaly trending NW-SE, and from east by a N-S trending linear contour lines. It is bordered from north by Bardarash anticline high (H1).
- Kalak Low (L3): This anomaly is in the southern part of the study area, extending from west to east and passing the southern part of the Kalak Town. Its minimum gravity value is about (-60mGal). It is bordered from the north by linear contours trending N-S. The positive anomaly can be seen in the west of Tobzawa district extending to the east and passes the Jideda village.

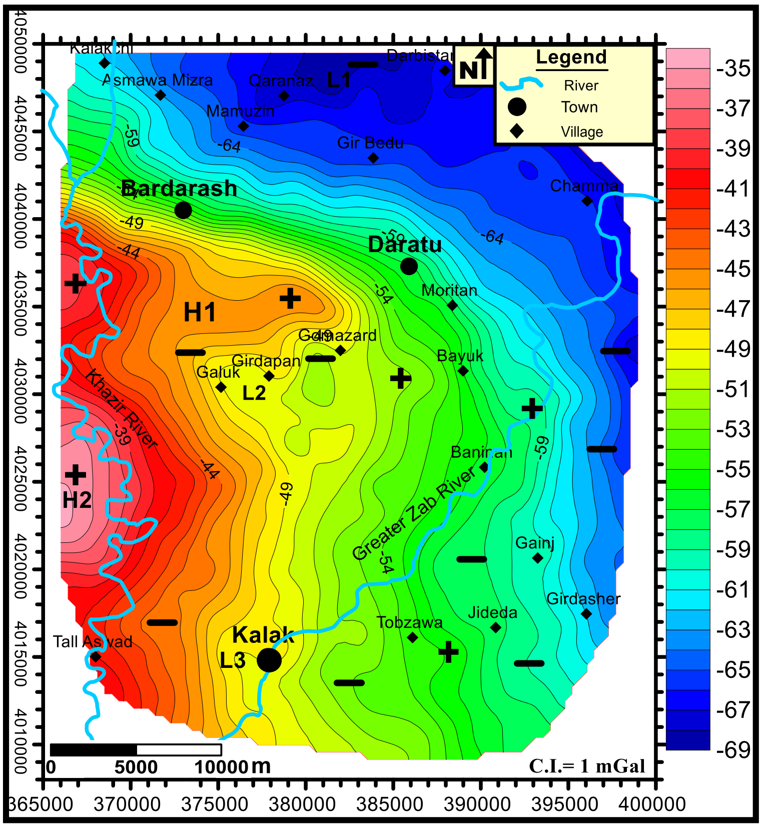

Figure 8: Bouguer anomaly map

The contour lines in the central and southern parts of the study area are generally trending N-S with irregular and wavy shapes. In the northern part, the contours are generally trending NW-SE that is coinciding with the gravity surveys that were carried out by (Al-Majid, 2013) in the northwestern part of the study area, which generally has also a NW-SE trending anomalies.

6.2 Transformed Maps

Bouguer anomalies are often characterized by a broad, gently varying, regional anomaly on which may be superimposed shorter wavelength local anomalies. Usually in gravity surveying it is the local anomalies that are of prime interest and the first step in interpretation is the removal of the regional field to isolate the residual anomalies (Keary & Brooks, 2002).

Among the most difficult issues in gravity data interpretation is the separation of residuals from their regional background. Two methods of separation (Griffin, 1949 and Surfer software) are used in this study to anomalies. The results are given in figures 9 and 10; they represent regionals and residuals.

Regional anomaly maps (Figure 9) show that the western and southwestern parts have the highest gravity values that reache -41mGal and decrease towards north, northeast and east. The lowest value is about (-67mGal) in the northeastern parts. Generally, the regional anomaly contour values slop towards the northeast direction which is the general slope of the basement rocks with a considerable gradient of 8 mGal/Km (i.e. deepening of the basement complex towards this direction).

The bending of the contour bands from N-S direction in the southern part of the area to NW-SE in the northern part, in such a way to show a positive, two dimensional nose-anomaly trending in the NE-

SW direction parallel to the course of the Zab river in this area. To show that obviously, a second order separation by hand smoothing technique was carried out for this positive anomaly (the upper box in figure 9). The result is a conspicuous E-NE positive anomaly with an amplitude of 3 mGal. It is a two-dimensional anomaly extending for about two kilometers and may extend out the scope of this study area.

The residual anomaly map on the other hand (Figure 10) is the important component of the Bouguer Anomaly map which reflects the local fields of near surface structures. It is obtained by removing the regional trends due to deep seated rocks.

The residual map when using the Griffin's method shows many positive and negative anomalies of different shapes and trends. The highest anomaly value is about (+10mGal) that is located in the southwest of Bardarash town while the lowest value is about (-6mGal) that is located in the northwestern corner of the map. The residual anomaly map of surfer program has the highest value of (7mGal) and lowest value of (-5mGal) at the same locations.

The five anomalies present on the residual anomaly map can easily be compared with those shown on Bouguer anomaly map; they are two positive; Bardarash (H1) and Ain-Alsafra (H2) while the other three are negative, Mamuzin (L1), Galuk (L2) and Kalak (L3).

7. Geological Implications

The geological map of the study area shows many surficial features such as different rock formations, rivers, folds, and faults. When overlying the Bouguer and residual anomalies on the geological map (Figures 11a and b respectively), the high gravity values are coinciding with anticlines such as Bardarash and Ain Al-Safra anticlines, while low gravity values are coinciding with synclinal plain areas such as Galuk Syncline, Kalak and Mamuzin plains. The area of these three gravity lows are mainly covered by residual soil deposits, flood plain deposits and river terraces.

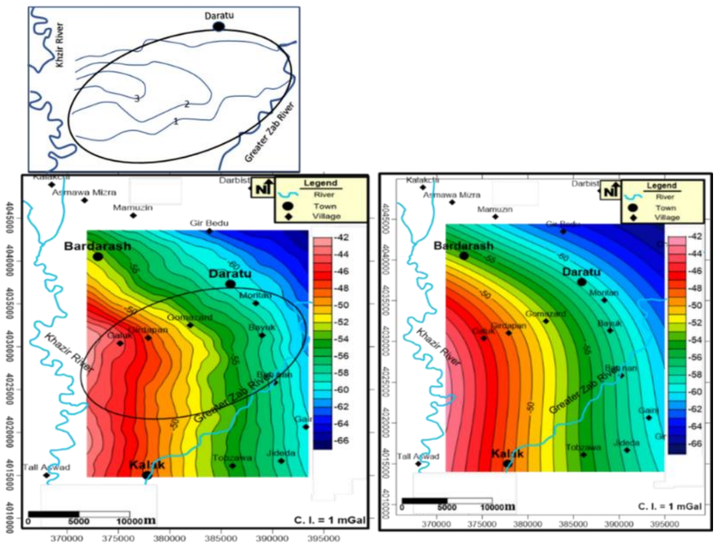

Figure 9: Regional anomaly maps, Griffin's method, 1949 (left)

and Surfer Program (right)

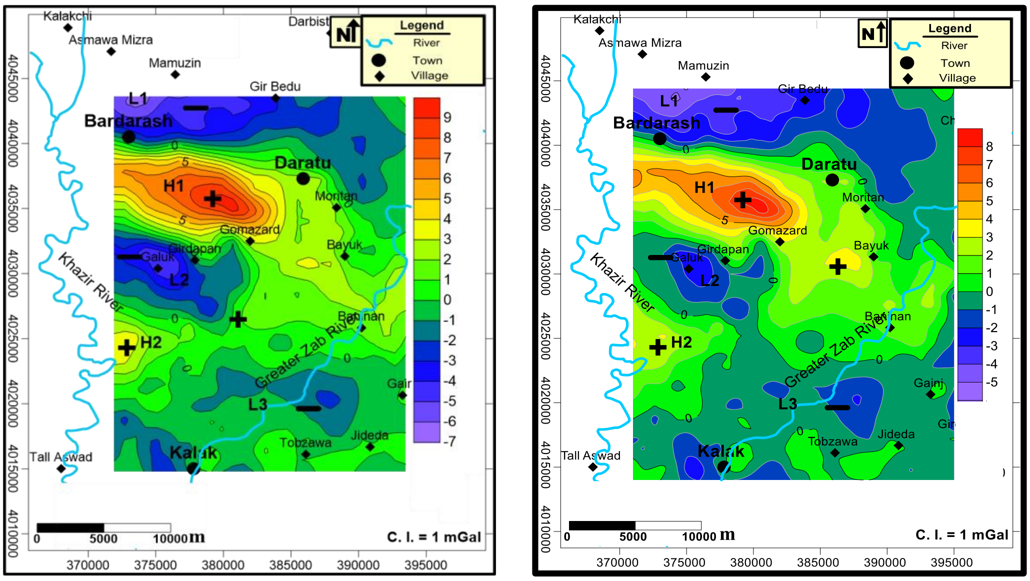

Figure 10: Residual anomaly maps, Griffin's method, 1949 (right)

and Surfer Program (left)

The Bardarash and Ain Al-Safra structures which cause the two gravity highs (Bardarash & Ain Alsafra) are mainly composed of PilaSpi, Lower Fars, Upper Fars, Lower Bakhtiari and Upper Bakhtiari Formations. These formations are composed of limestone, sandstone, claystone and conglomerate rocks.

One important feature is observed in figure 10a; that is the shift of the Bardarash Anticline's axis towards northeast as interpreted from gravity data. This might mean that the fold axial plane is inclined towards northeast since the gravity anomalies reflect the subsurface situation while the fold axis plotted on the geological map is a surficial feature.

Figures (10a and b) show that the gravity values decrease rapidly on both sides of Bardarash high especially on the northern side for Bouguer data and both sides of the residual. This can be interpreted geologically as two faults trending (ESE-WNW) bounding the anticline from north and south. The gravity values decrease from west to east of the map in figure 10a. Almost all contour lines running from south to north, suffer bending in a systematic manner. All these bindings follow both the Khazer and Zab rivers course. This can also be interpreted as to be caused by two faults following the two courses (zones K and Z in figures 10a and 10b). The fault along Zone (K) is well defined by (Ghaib & Al-Dawoody 2010). They concluded that it is a NE-trending basement fault that extends for ~ 140 km along the course of the Greater Zab River. Also, a map of basement faults was published by (Zebari & Burbarry, 2015) showed almost the same results regarding the Greater Zab fault. Their study depended upon combining both structural and geomorphological methodology. The Greater Zab and Khazir Rivers show meandering shapes on surface; which may be due to shallower structures related possibly to the type of sedimentary rocks on the surface (mainly Upper Bakhtiari Formation), reflected as wavy contour lines on the Bouguer and Residual Anomaly maps.

Composition, internal structure, depth, and morphology of the basement rocks of Iraq are questions, which have no direct answers. These rocks do not crop out and no deep holes have so far penetrated them. The interface between the basement rocks and sedimentary cover in northern Iraq dips toward the east and southeast (Ghaib, 200; Numan & Ghaib, 2019). Ditmar et al. (1971) prepared a basement relief map of Iraq based on gravity data while Buday and Jassim (1987) summarized the studies on the Iraqi basement and published three different maps showing the relief of the basement depending upon gravity and magnetic data. These maps do not cover the area of this study. However, the extrapolation of those maps gives an indecisive range of depth from 7 to 13 km in the Erbil area (including the present study area). The gravity data alone cannot give a precise basement depth; they do, however, give an approximate depth. Many authors, to calculate the depth of basement have suggested the well-known formula of Bouguer slab. It has been applied in this study to calculate the depth to the basement by postulating the sedimentary cover as an infinite slab (Figure 11).

The density contrast between the basement rocks and sedimentary cover, as mentioned before was taken to be 0.18gm/cm3. Figure 12 reveals that the basement rock has depths ranging from 5900m at the southwest and 8600m at the northeast. Hence the basement rocks are deepening towards east and northeast. About 30 kilometers to the southeast, Ghaib, 2011 and Numan and Ghaib, 2019 found that the depth of basement is ranging between 7000m and 9000m in Erbil plain area, while it is between 5000m and 6000m in the Aqra plain some 35 kilometers to the north of the present study area. The author believes that the Bouguer anomalies when used in calculating the basement depth (as done in this study) give rise to an overestimated value because the Bouguer values include gravity effects that come from the sedimentary cover. Because of that the regional anomaly map was used to do that. There are indeed no techniques, which separate residuals and regionals perfectly. The interpretation of these data should be subjected to the control of the seismic evidence where the latter is available.

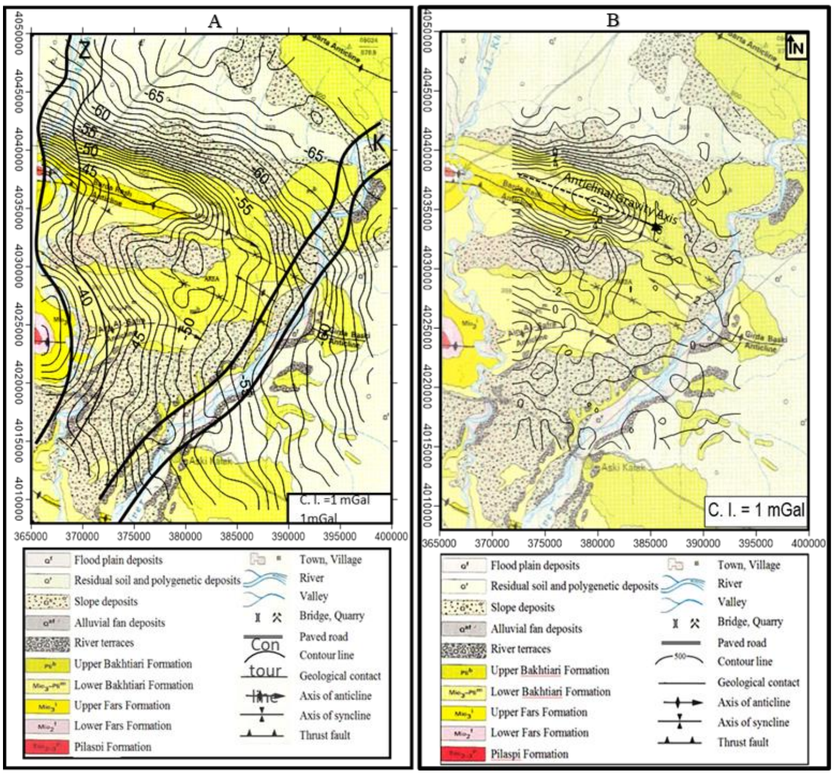

Figure 11: (a) Bouguer anomalies superimposed on geological map

(b) Residual anomalies superimposed on geological map

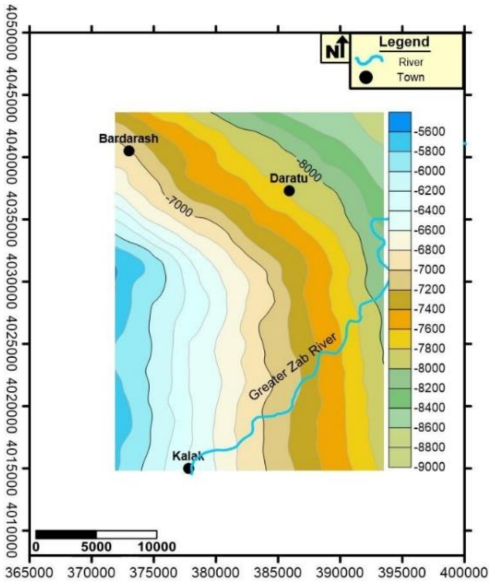

Figure 12: Basement depth map

A (E-NE) positive anomaly is isolated manually from the regional anomaly map (the upper box in figure 9). It has an amplitude of 3 mGal and it is almost parallel to the course of the Zab river and makes a northern boundary of the river. This may indicate the tectonic effect on the course of this river as mentioned earlier by (Numan, 1984).

8. Gravity Anomaly and Landsat lineaments

It is generally accepted that the basement rocks in Iraq comprise blocks of various dimensions. These blocks are separated by faults of different trends depending upon the geologic history in a particular area of study. The basement faults have their effect on the sedimentary cover during the tectonic history. These faults are usually reflected on the gravity maps or profiles since they lead to a considerable lateral density variation. The extension of the faults, their orientation and the position of the downthrown side is determined by their effects on the gravity contour lines.

The linear contour line anomalies of the gravity maps show some trends that can be correlated with faults in the area. Visually nine trends are estimated in the Bouguer and Residual Anomaly maps in the study area. The major faults that trend in NE-SW and N-S directions are coinciding with the main trends of the Greater Zab and Khazir Rivers respectively. The others are trending NE-SW and NW-SE (Figure 13).

A lineament map of the area is constructed using the Landsat image (Reber Ali and Soran Hasan, personal communication, 2017). The trends deduced from the Bouguer and Residual Anomaly maps were superimposed on this map and shown in Figure (13).

There is a reliable coincidence between some of the gravity trends and Landsat lineament in both position and direction as shown in the rose diagrams (right down corner of the figure). The inconsistency in others comes from that gravity trends mainly reflect the subsurface variations while the lineaments represent surface features which may have been also coming from deep seated sources and have been shifted in terms of depth due to some tectonic, structural or geomorphological reasons.

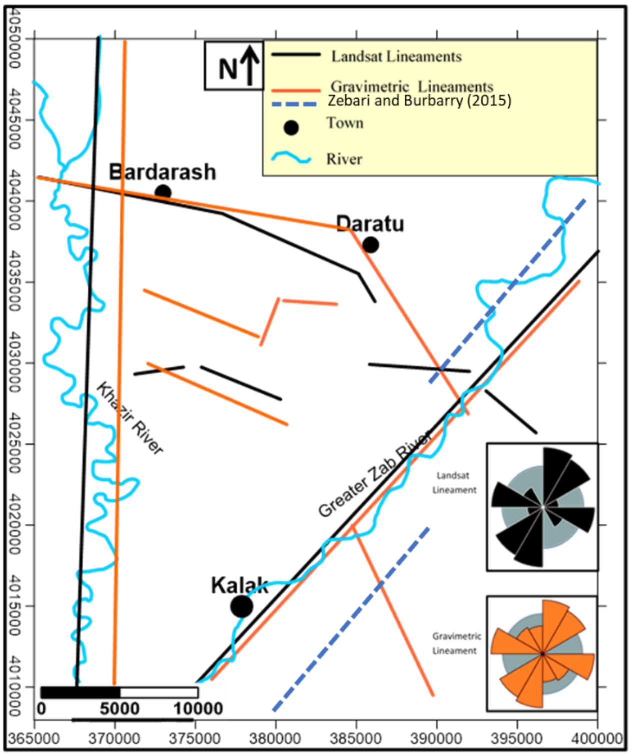

Figure 13: Gravity and Landsat lineaments

9. Conclusions

Based on this study, the following conclusions can be made:

- The first inspection of the Bouguer anomaly map shows that gravity values decrease from west and southwest towards east, northeast, and north. The lowest gravity values were shown in the northeast sector reaching -69 mGal, while the highest values are present in the west reaching -35 mGal. The horizontal gradient from west to east was about 0.9 mGal/km and from southwest to northeast was about 1.1 mGal/Km. Five major positive and negative anomalies were found; they are Bardarash High (H1), Ain Al-Safra (Zardik) High (H2), Mamuzin Low (L1), Galuk Low (L2) and lastly Kalak Low (L3).
- In order to show the effects which are likely to be associated with the geological features of interest, the Bouguer anomalies were separated into their Regional and Residual anomaly components. After the visual inspections and interpretations, the Bouguer and Residual anomaly maps were superimposed on the geological map to make a comparison between the gravity field and surface geological features. This process revealed that the gravity values decrease rapidly on both sides of Bardarash anticlinal structure, especially on the northern side for Bouguer data and both sides for the residual data. This can be interpreted geologically as two faults trending (ESE-WNW) bounding the main anticline from north and south. Almost all contour lines which run from south to north, suffer undulations in a systematic manner and following both the Khazer and Zab rivers course. This can also be interpreted as two faults following the two river courses.
- The density contrast between the basement rocks and sedimentary cover, was considered to be 0.18 gm/cm3. The basement rocks depth had been calculated. They range between 5900m at the southwest and 8600m at the northeast. Hence the basement rocks are deepening towards

east and northeast. This direction of slopping of the basement was mentioned by many other authors around the area of study.

- Visually nine linear trends were estimated in the Bouguer and Residual Anomaly maps in the study area. Two of these trends were considered as major faults that trend in NE-SW and N-S directions. They were coinciding with the main trends of the Greater Zab and Khazir Rivers. The others are trending NE-SW and NW-SE. There was a reliable coincidence between some of the gravity trends and Landsat lineament in both position and direction. The inconsistency in others comes from that gravity trends mainly reflect the subsurface variations while the lineaments represent surface features which may have been also coming from deep seated sources and have been shifted in terms of depth due to some tectonic, structural or geomorphological reasons.

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