A New Comprehension of the Basement Undulation in North Iraq Resorting to Geomagnetic Investigation

Jeomanyetik Araştırmayla Kuzey Irak'taki Temel Ondülasyonu İçin Yeni Bir Anlayış

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Abstract: Because there are no wells in Iraq that go down to the basement complex of igneous and metamorphic rocks which are thought to be aggregated during the Late Precambrian, so the current study is important in tracking the surface boundary with the sedimentary cover and try to identify the structural appearance and the effect of this in construction of the geological situation in the region. The geophysical survey included 87 magnetic measurements with implantation the required corrections as well as using the upward continuation to remove the noises that not required in the present study.

A quantitative interpretation has been made using Oasis Montaj program across five magnetic profiles (Tr1, Tr2, Tr3, Tr4, and Tr5) with control of well logging, gravity, and seismic information. The results showed varying depths of the basement rocks ranging from 10 km in the northeastern part (Aqra structure) to less than 6 km in the south-west of the study area. In addition, a number of grabens, half grabens and horsts have been simulated in the magnetic sections for the present study.

Keywords: Magnetic survey, Basement rocks, Oasis Montaj, 2D modeling, Northern Iraq

Öz: *Irak'ta, Geç Prekambriyen dönemine ait olduğu düşünülen magmatik ve metamorfik kayalardan oluşan temel kompleksine kadar inen hiçbir sondaj kuyusu bulunmadığından dolayı, bu çalışma; tortul istifle olan sınırı ve yapısal nitelikleri izlemek ve bölgedeki jeolojik gelişimin anlaşılması açısından önemlidir. Jeofizik araştırmada 87 manyetik ölçü alınmıştır, verilere gerekli düzeltmelerin yanında bu çalışma kapsamında olmayan ve gürültü olarak nitelendirilebilecek etkiler yukarı analitik uzanım tekniğiyle giderilmiştir.*

Beş adet manyetik profil verisi için (Tr1, Tr2, Tr3, Tr4 ve Tr5) kuyu logu, gravite ve sismik bilgilerin kontrolünde Oasis Montaj programı kullanılarak nicel bir yorumlama yapılmıştır. Sonuçlar, temel kayaların çalışma alanının kuzeydoğu kesiminde (Aqra yapısı) 10 km'den çalışma alanının güneybatısındaki 6 km'den daha düşük bir seviyeye kadar değişen derinliklerini göstermiştir. Ayrıca, bu çalışmada manyetik kesitlerde bir dizi graben, yarı-graben ve horst simüle edilmiştir.

Anahtar Kelimeler: *Manyetik araştırma, Temel kayalar, Oasis Montaj, 2B Modelleme, Kuzey Irak*

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INTRODUCTION

The geomagnetic technique is usually used as a reconnaissance method to derive the architectural style of the basement complex surface which reflects the formation of the sedimentary basins that are very important in the accumulation of hydrocarbon recourses. The mathematical expressions of the geomagnetic method are more complex than other potential approaches due to variation of the magnetic vector elements of the dipolar properties and the wide range of magnetic susceptibility. The purpose of the magnetic method is to determine the spatial variation of the geomagnetic field in the survey area and use these variations to deduce the geometry, depth and magnetic characteristics of subsurface rocks. The sedimentary rocks always are so much less magnetic than the underlying basement, usually igneous or metamorphic rocks, that the magnetic effects are almost the same as if the sediments were not present (Nettleton, 1976).

The magnetization of rocks has both direction and magnitude and can be a combination of both remnant and induced magnetization. The induced magnetization which is often the most important component within a source body depends on the rocks magnetic susceptibility that is the degree of the ease with which a rock may be magnetized when induced by an external magnetic field. On the other hand, the remnant magnetization depends on the history of the rock solidification. The distortion of polarization by remnant magnetization is not regular or consistent enough to cause serious problems in magnetic interpretation. However, the remnant magnetization of the Iraqi basement seems to be in the normal direction of the present geomagnetic field rather than in reverse (Baban, 1983).

The area is located in Northern Iraq within the foot hill and high folded zones bounded by longitudes 42°36'E – 43°34'E and latitudes 36°51'N – 37°14'N. It includes a number of low and high mountains (Kand, Dahkan, Alqush, Shaikhan, Duhok, Bekher, Atrush, Birifka, Chia Gara, Maten, Aqra, Piris and Barat; Figure 1). The magnetic stations were selected to pass a number of anticlines such as (Bekher, Shaikhan, Aqra, Piris).

Mutib et al. (2019) identified several grabens, half grabens and horsts from the modeled profiles, surrounded by normal and reverse faults which displayed in the sedimentary sections by gravity "lows" and "highs" across Aqra anticline.

Al-Brifkani (2008) has already set a schedule of the outcropping geological formations nearby the study area showed their thicknesses, ages and lithology (Table 1).
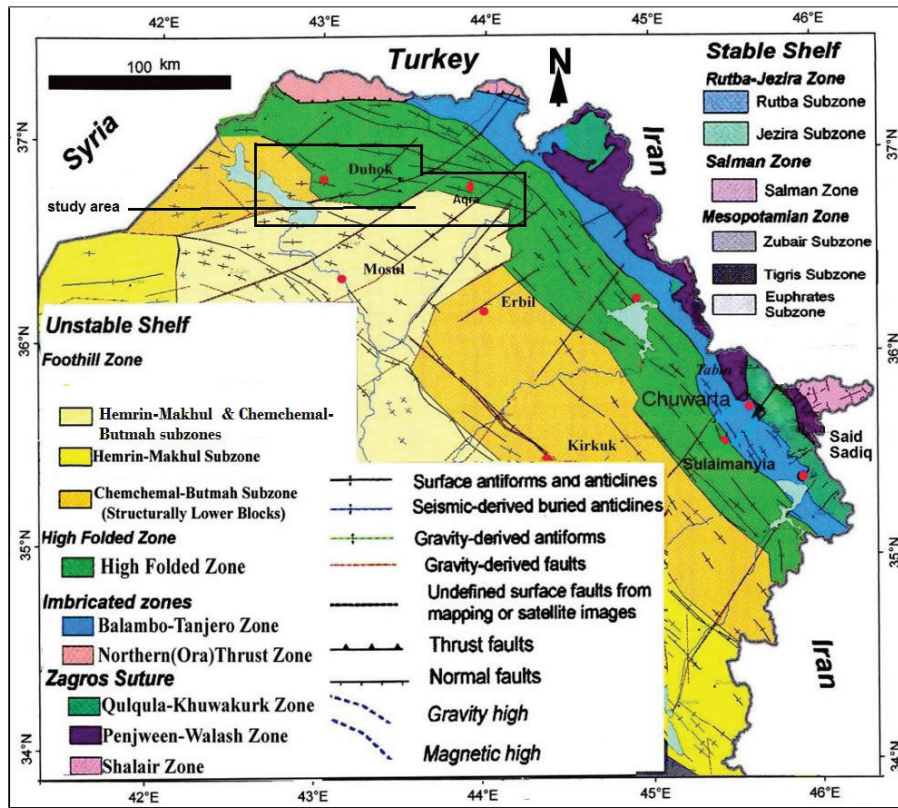
Figure 1. Tectonic zones and structural elements of unstable shelf (Jassim and Goff, 2006) with the location of the study region.

Şekil 1. *Çalışma alanının konumu ile duraysız şelfteki tektonik zonlar ve yapısal unsurlar.*

MATERIALS AND METHODS
Magnetic Data Correction

The present field magnetic measurements were exposed to filter the different unwanted sources as magnetic noises such as cars, railways, pipe-lines … etc as well as removals of the diurnal variation in the earth's magnetic field. It was thus important to establish a local base station in a magnetically quiet area and re-visited within one hour as recommended by Reynolds (2003).

The normal field correction was performed by subtracting the theoretical field obtained by the International Geomagnetic Reference Field (IGRF), from the corrected magnetic observations. This correction can be implemented from published map and tables or from certain site (www.ngdc.noaa.gov/geomag/calculators). In the current study we did not need to correct the magnetic terrains (e.g., over lava flows or mineralized intrusions) because they do not exist (Lowrie, 2007).

Table 1. The outcropped formations in the study area from their typical locations after (Al-Brifkani, 2008).

Çizelge 1. Tip lokasyonlarından, çalışma alanında yüzeyleyen formasyonlar (Al-Brifkani, 2008).

ERA	PERIOD	EPOCH	FORMATION	THICKNESS	DESCRIPTION
Cenozoic	Pliocene		Bakhtiari		Claystone, silty pebbly conglomerate, conglomerate.
	Miocene	M-U	Fars Group		Marl, claystone, sandstone
	Eocene	M-U	Pilaspi Limestone	85 m	White chalky limestone partly dolomitic, recrystallized karstic in places, porous
	Eocene	M	Gercus	838 m	Moderately compact claystone -partly fissile silty with thin beds of green marl, plastic and thin horizon of conglomerate massive, brecciated sandy and white slightly hard gypsum layers and nodules
	Paleocene-Eocene	UP-LE	Kolosh	777 m	Highly deformed silty claystone mainly green
Mesozoic	Cretaceous	U	Hadiena	755 m	Conglomeratic, fragmental and brecciated limestones alternating with fragmental shelly limestone with frequent hematite breccias and calcareous marls, ferruginous.
	Cretaceous	U	Bechma Limestone	315 m	Well bedded massive white-buff, fractured limestone
	Cretaceous	L	Qamchuqa Limestone	799 m	Massive dolomitic limestone at top, recrystallized, fossiliferous, karstified
	Jurassic-Cretaceous	UJ-LC	Chia Gara	232 m	Thin beds of limestone and yellowish marly limestone with shale at top
	Triassic	U	Kurra China	835 m	Dark brown black limestone alternated with dolomite, pyritic and fissile shale with slump structure with gypsum beds at the bottom croped out at the Turkey border
	Triassic	M	Geli Khana	875 m	Dolomite, ferroginous with black chert, dolomitic limestone and shale
	Triassic	L	Beduh Shale	64 m	Shale, reddish brown, fissile with marl and limestone
	Triassic	L	Mirga Mir	200 m	Marly limestone, grey, oolitic silty at bottom
Paleozoic	Permian	U	Chia Zairi	811 m	Dark blue limestone, thin bedded detrital with silicified limestone, hard massive with chert nodules
	Carboniferous	L	Harur Limestone	62 m	Black organic limestone, thin bedded, detrital, intercalated with micaceous shale
	Carboniferous	L	Ora Shale	215 m	Black mica and calcareous shale with olive green marl and thin detrital limestone
	Devonian	U	Kaista	30 m	Dark blue argillaceous limestone, silty shale and streak of sandstone
	Ordovician		Chalki Volcanics	16 m	Dull greenish grey, red, white-olive basalt and soft red silt
	Ordovician		Pirispiki Red Beds	80 m	White massive cross bedded quartzite slightly reddish marl and sandstone, conglomerate lenticles and red shale.
	Ordovician		Khabour Quartzite Shale	800 m	Alternation of thin bedded fine grained sandstone, quartzite and silty micaceous shale, olive green -brown slightly metamorphosed

The proton precession magnetometer was applied to record the measurements. The type of device utilizes the precession of spinning protons or nuclei of the hydrogen atom in a sample of hydrocarbon fluid to measure only the total magnetic intensity within ± one nT. The sensor was kept within one elevation (250 cm) above the ground surface throughout the survey so as not to be affected by magnetic objects scattered on the surface of the earth (Reynolds, 2003). The instrument showed a reasonable changing during the period of the field work (November-December, 2010) (Figure 2).
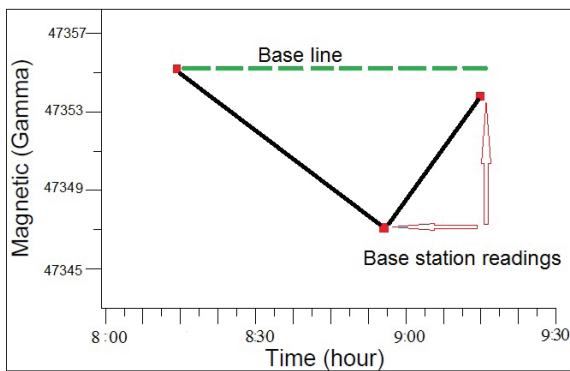
Figure 2. Diurnal curve for one-day magnetic work 20/11/20.

Şekil 2. Bir günlük manyetik çalışma için günlük eğri 20/11/20.

To facilitate the fieldwork survey, the magnetic stations were installed depending on the feasibility of access and the spacing distances which were necessary in detail the features underneath, minimize the costs and speed-up the fieldwork. The co-ordinations and altitudes of the stations were recorded from Garnet instrument and therefore the lengths of the profiles were determined and plotted using DEM and the spacing between stations ranged between 500 and 5000 m.

The magnetic data were represented as the differences (Δ mag) between the relative measurements of the stations in the network and certain station (base-station) (Parasnis, 1997). Rock Susceptibility is the ratio of the induced magnetization value over external magnetizing field with dimensionless units. It forms the fundamental parameter in magnetic prospecting since the magnetic response of rocks and minerals is determined by the amount of magnetic materials in them.

Data Processing

There are several techniques for decomposition of a magnetic anomaly profile across the study structure. They range in complication from simple visual inspection of the anomaly pattern to advanced mathematical analysis (Lowrie, 2007).

The optimum upward continuation height was adopted in the present study using the experimental method by the correlation coefficient calculation (r) between the upward continuity at two sequential heights. The correlation coefficient is plotted as a function of continuation height increasing from zero to a level where the change in correlation coefficient values has clearly passed the point giving rise to a maximum deflection (Zeng et al., 2007). The height that gives the maximum deflection is the most appropriate height value (Figure 3).
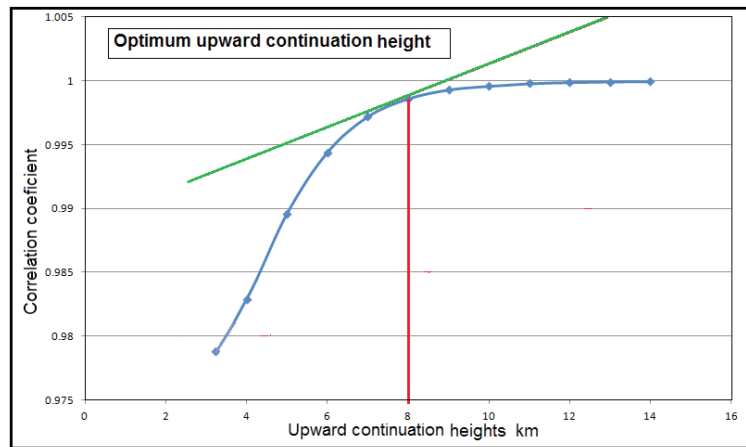
Figure 3. Cross-correlation between continuations of two successive upward heights versus the upward heights for one of magnetic profiles in the study area (Tr5).

Şekil 3. *2 ardışık uzanım yükseklikleri ile çalışma alanındaki manyetik profillerden birinin (Tr5) uzanım yüksekliği arasındaki çapraz ilişki.*

Simulation Models

The design procedure of the models is based on interpreter experience and is produced from given anomalies resorting to their appearance and relations with the geology information over studied features. The qualitative models are tested and may be verified or falsified depending on the inventive imagination and a good geological information. The interpreter should use the easy estimation and a large number of possibilities and finding a suitable design. The interpretation includes also methodological aspects and an assessment of geological implications (Jacoby and Smilde, 2009).

Three steps were carried out according to the international references in the current study. The first step in the quantitative interpretation is the visual inspection of the station locations to choose the profile that crosses the interesting anomaly. The second is the estimation of the horizontal extension, depth, shape and thickness of the target by using a geological information (well logging, seismic sections, previous gravity studies; Al-Brifkani, 2008; Kent, 2010; Gulf Keystone, 2010). And the third is to establish a geometric model

which satisfies the above mentioned estimations and agrees with the geologic situation by using a recent computer programming (Geosoft, 2008).

Then the magnetic models were calculated based on Talwani, et al. (1959), Marqardt inversion algorithm and developed by the USGS with their computer program (Webring, 1985). GM-SYS is using a two-dimensional model for the magnetic calculations; which is, each structural unit expands to plus and minus infinity in the direction perpendicular to the profile with assuming that the earth to have no curvature. So, the model should extend plus and minus 30,000 kilometers along the profile to avoid edge effects.

Because the modeling software requires profiles with straight lines (according to Geosoft, program), a kriging grid was applied for each survey line using all magnetic stations which were projected perpendicularly onto this line, and the distances were always calculated from the first southernmost station on each line.

The susceptibility of different rock units of the causative bodies and the surroundings should be known as precisely as possible in order to calculate the contrast for both of the preliminary

estimations and the final calculations (Jacoby and Smilde, 2009).

In the present study, the geometrical models are also controlled with local seismic studies. The first model was performed along Bashiqa - Kand traverse which defined the causative faults of Bashiqa and Kand anticlines as shown in Figure 4 and using the seismic control from Kent (2010). The second was deduced passed along Shaikhan anticline and clarified two reverse faults (Figure 5) and depending on the seismic control of the Gulf Keyston (2010). Furthermore, all previous gravity, lithostratigraphic and structural studies were also taken into account to produce those models.
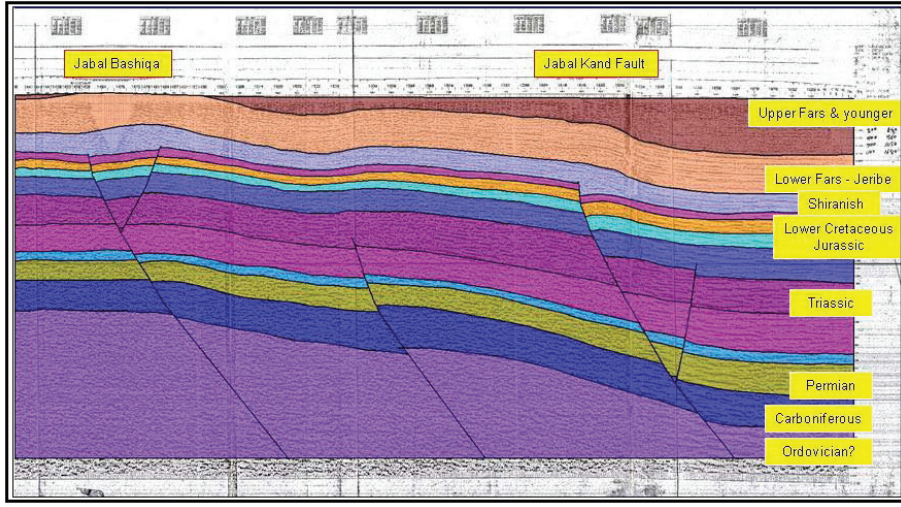
Figure 4. The seismic line passes the plunges of Kand and Bashiqa anticline (Kent, 2010).
Şekil 4. Kand ve Bashiqa antiklinali dalımlı ekseninden geçen sismik hat (Kent, 2010).
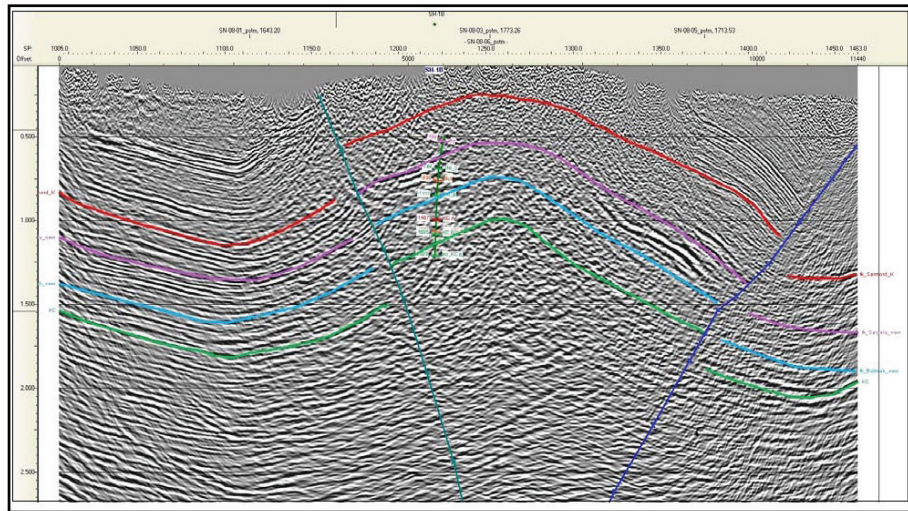
Figure 5. A north-south section of the Shaikan anticline and interpreted reflectors of a seismic line SN-08-06. The well depth is 1.25km (Gulf Keystone, 2010).
Şekil 5. Shaikan antiklinalinin kuzey-güney kesiti ve SN-08-06 sismik hattının yansıtıcılarının yorumu. Kuyu derinliği 1,25 km (Gulf Keystone, 2010).

RESULTS
Magnetic Profiles

Three magnetic susceptibility values for three layers (basement rocks, sedimentary cover without Gercus formation, and Gercus formation) were used to generate the required model of the profiles Tr1, Tr2, and Tr3. In contrast, the models of profiles Tr4, and Tr5 adopted two values of magnetic susceptibility for two layers (basement rocks, and sedimentary cover without Gercus formation) to recognize the basement rocks and their overlaying sedimentary cover. Specifications of the third Gercus rocks layers which constitute from red bed claystone have been taken into account in construction the models in the studied area which varies from place to place according to Hussain (2012). The Magnetic susceptibility contrast with value of 0.0013 emu/cc between basement rocks and sedimentary cover was taken in the study models, while 0.0001 emu/cc was used between Gercus formation and its surrounded rocks (Al-Shaikh et al., 1997). The normal magnetic field T, declination D and Inclination I were obtained from IGRF program with values of 47000 nT, 5°, 55° respectively.

The isolation of the residuals from the regional magnetic field in the study area was performed using the upward continuation empirical approach mentioned above (Zeng et al., 2007). Then, the produced upward continuation height was applied to obtain five models of residual magnetic profiles for the study area. Table 2 shows the optimum upward continuation heights that applied to obtain the residual magnetic profiles and the locations of magnetic profiles were drawn Appling DEM (Figure 6).

Table 2. The optimum upward continuation heights applied to obtain the residual magnetic profiles.
***Çizelge 2.** Rezidüel manyetik profilleri elde etmek için uygulanan optimum yukarı uzanım yükseklikleri.*

Profile	Optimum upward height (km)
Tr1	6
Tr2	6
Tr3	6
Tr4	6
Tr5	8
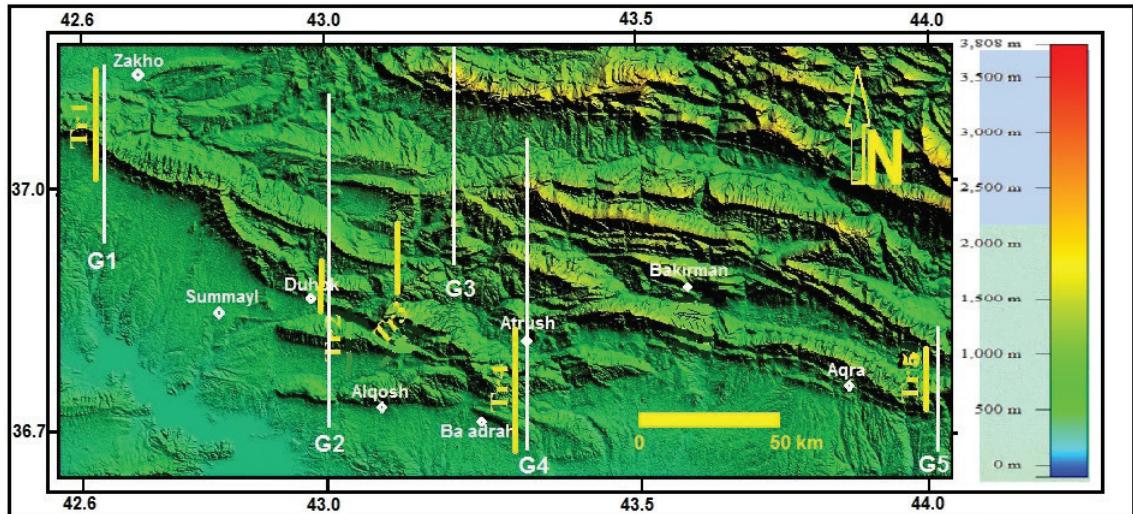
Figure 6. Locations of five magnetic (Tr) and gravity profiles (G) on the DEM.
***Şekil 6.** Beş manyetik (Tr) ve gravite (G) profilinin Sayısal Yükseklik Modeli (SYM) üzerindeki konumları.*

Residual Magnetic Anomalies

Profile Tr1

The profile shown in Figure 7 extends about 20 km and runs across Bekher anticline near Zakho city where it shows one negative anomaly located over Bekher anticline. The amplitude and half-width of this profile anomaly is approximately 32 nT and 3 km respectively. By comparison of this magnetic profile with the gravity profile (G1) established by Al-Majid, (2013) (Figure 8), the current anomaly is explained as two E-W normal faults**.**

Profile Tr2

Figure 9 displays the profile Tr2 extension (10.5 km) and also passes across Bekher anticline, as noted a positive anomaly located over this structure with amplitude of approximately 13 nT and 2 km half-width. This model was correlated with the gravity profile G2 (close to Tr2) derived from Al-Majid, (2013) (Figure 10), and it can be suggested as a horst with a set of NW-SE reverse faults.
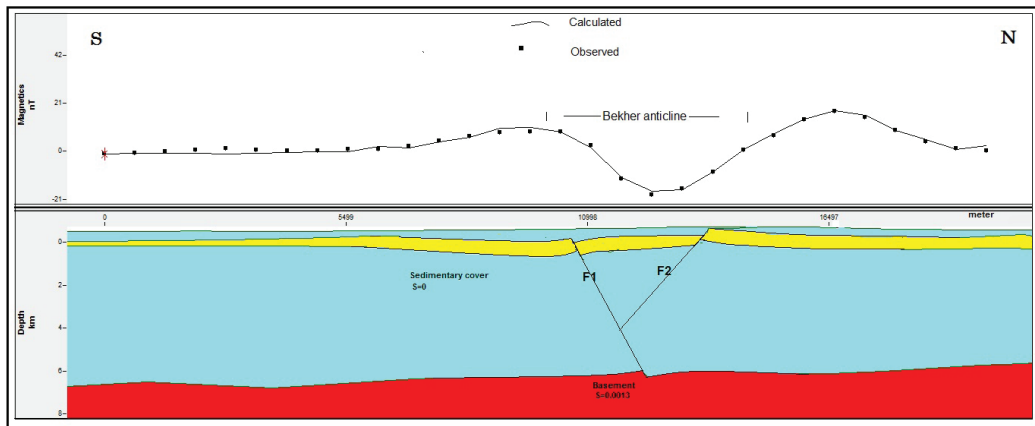

Figure 7. Cross-section and magnetic data along profile Tr1.

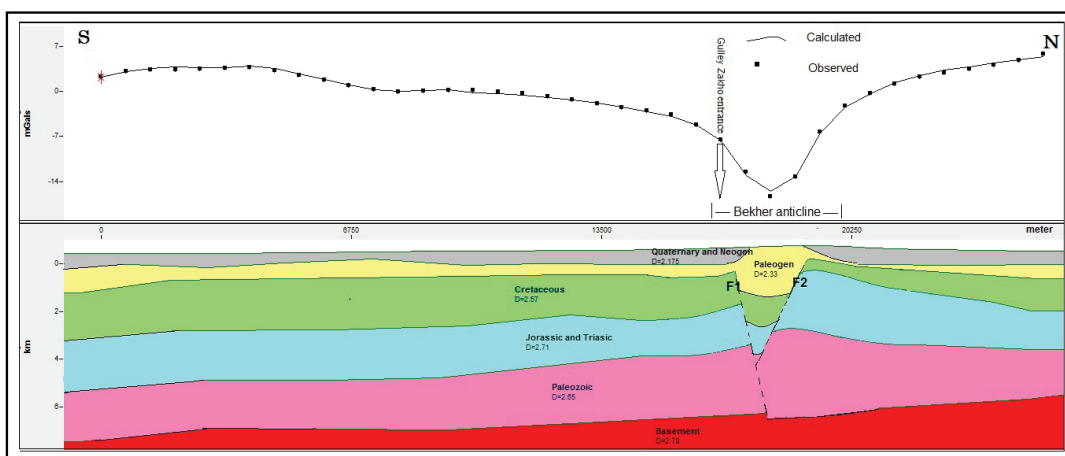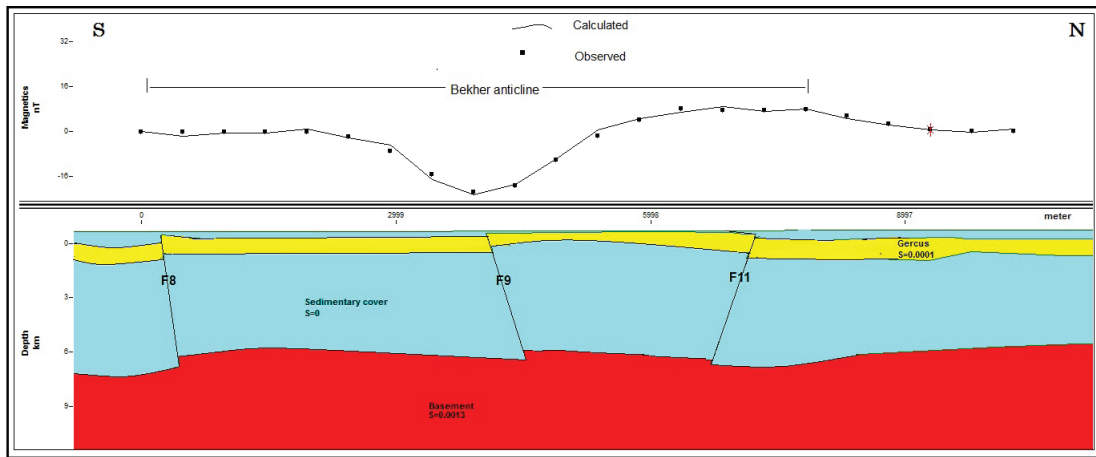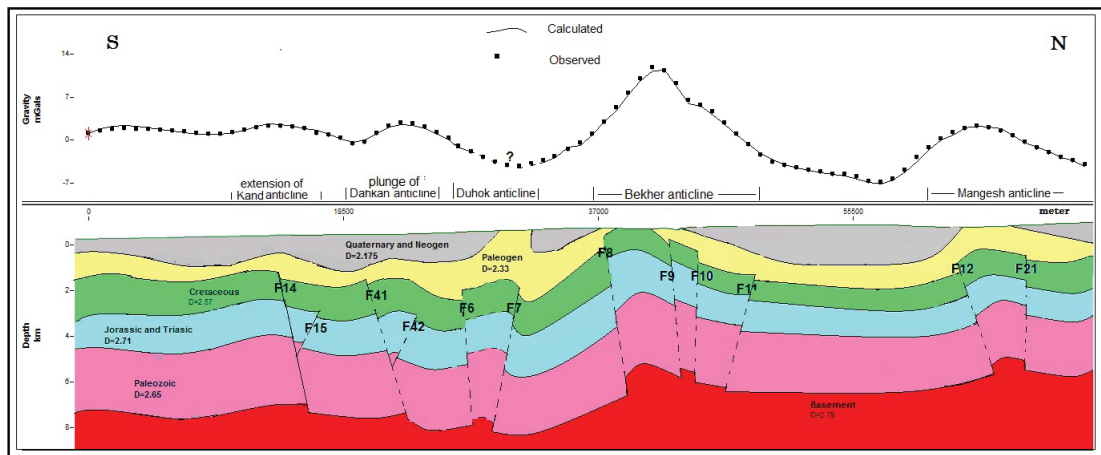*Şekil 7. Tr1 profili boyunca enine kesit ve manyetik veri.*

Figure 8. Cross-section over gravity data along profile G1(Al-Majid, 2013).

Şekil 8. G1 profili boyunca gravite verileri üzerinden enine kesit (Al-Majid, 2013).

Figure 9. Cross-section and magnetic data along profile Tr2.
Şekil 9. Tr2 profili boyunca enine kesit ve manyetik veri.

Figure 10. Cross-section over gravity data along profile G2 (Al-Majid, 2013).
Şekil 10. G2 profili boyunca gravite verileri üzerinden enine kesit (Al-Majid, 2013).

Profile Tr3

The profile plotted in Figure 11 extends for about 12 km to pass through the plunges of Bekher and ChiaGara anticlines. It illustrates two positive anomalies one of them was seen over the northern limb of Bekher anticline with amplitude and half-width of approximately 10 nT and 3.5 km respectively, and the other was located over the plunge of ChiaGara anticline. This model was derived with best compatible to gravity profile G3 which concluded by Al-Majid, (2013) (Figure 12).
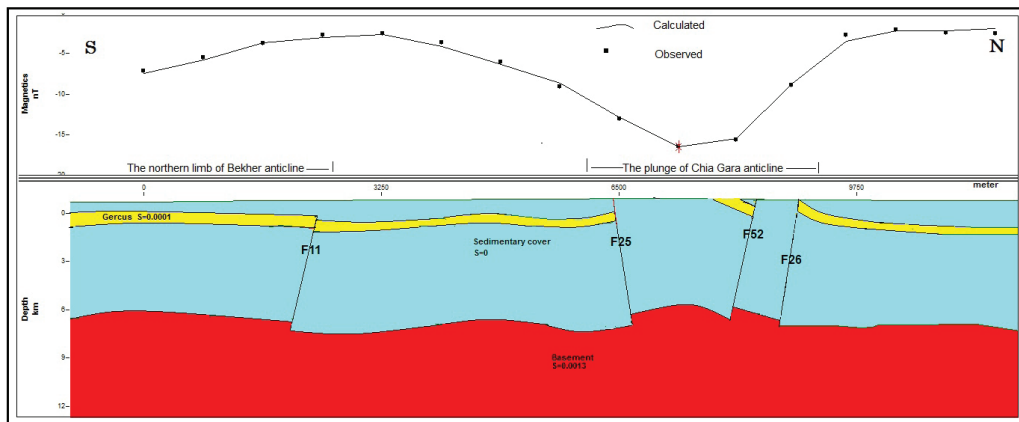
Figure 11. Cross-section and magnetic data along profile Tr3.
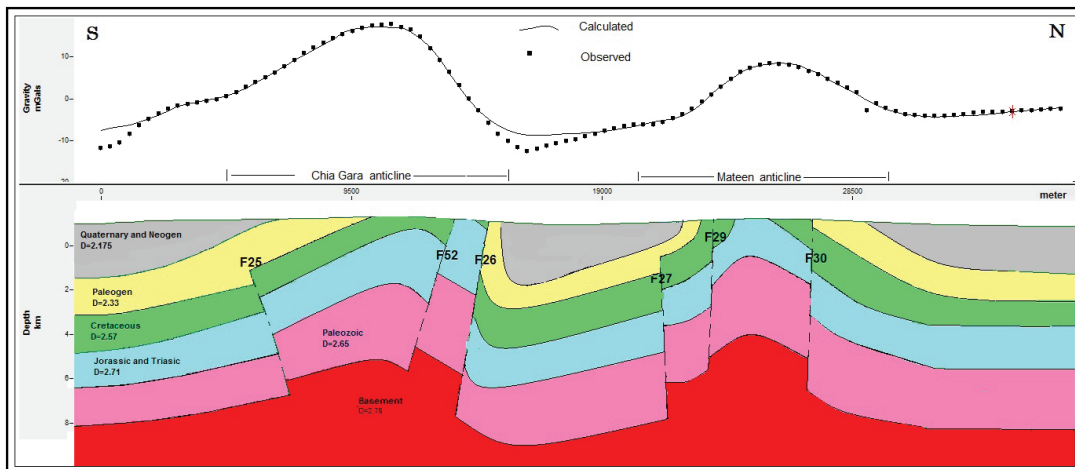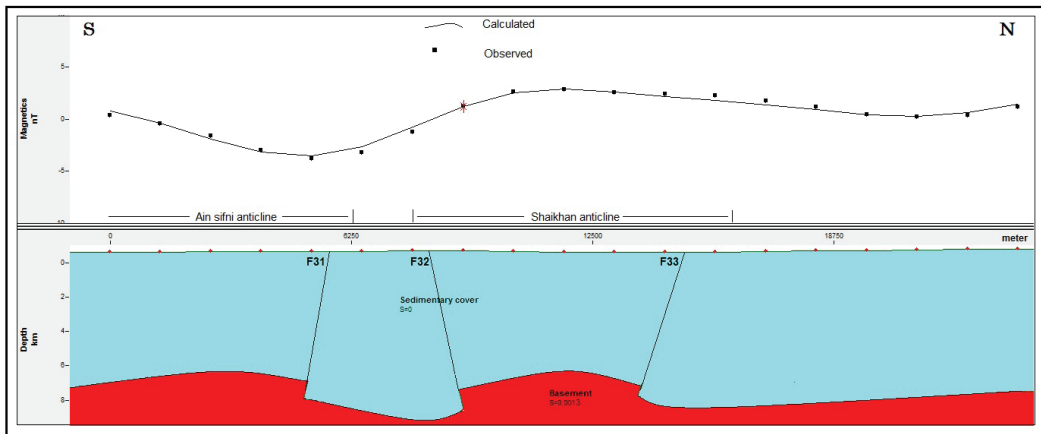*Şekil 11. Tr3 profili boyunca enine kesit ve manyetik veri.*

Figure 12. Cross-section over gravity data along profile G3 (Al-Majid, 2013).
Şekil 12. G3 profili boyunca gravite verileri üzerinden enine kesit (Al-Majid, 2013).

Profile Tr4

This profile runs across Shaikhan anticline with a length of about 23 km (Figure 13), and displays one positive anomaly located over this structure with amplitude of about 5 nT and 7 km half-width.

It was simulated depending on the seismic section shown in Figure 5 and the gravity profile G4 produced by Al-Majid, (2013) (Figure 14). The induced magnetization effect of Gercus formation did not appear in this profile due to its little thickness compared with the other profiles.

Figure 13. Cross-section and magnetic data along profile Tr4

Şekil 13. Tr4 profili boyunca enine kesit ve manyetik veri.

Figure 14. Cross-section over gravity data along profile G4 (Al-Majid, 2013).

Şekil 14. G4 profili boyunca gravite verileri üzerinden enine kesit (Al-Majid, 2013).
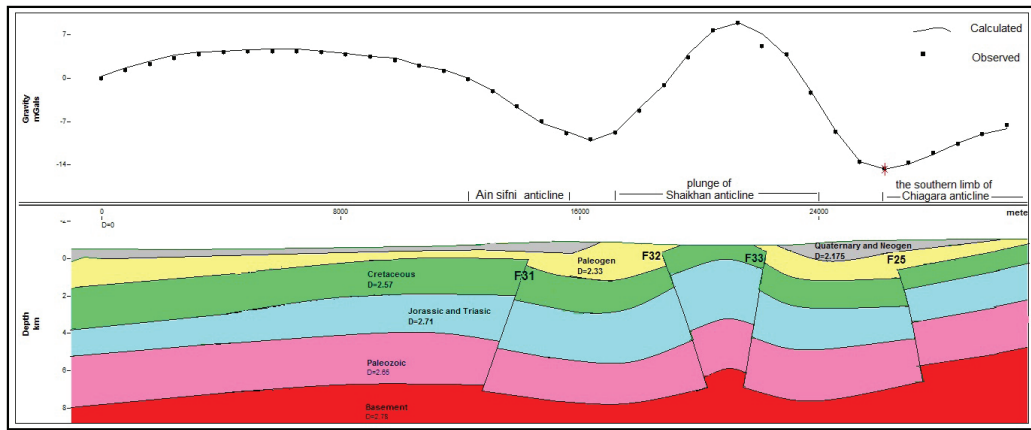
Profile Tr5

The profile stretches for about 23 km across Aqra anticline and the southern part of Piris anticlines (Figure 15) with positive and negative anomalies. The first positive anomaly locates over Aqra anticline with amplitude of about 20 nT and a half-width of approximately 4 km. This anomaly can be interpreted as a horst bounded by two E-W reverse faults, and two E-W normal faults divides the latest. The second one appears over the southern limb of Piris anticline with amplitude of about 30 nT and a half-width of approximately 4 km, and formed by an E-W reverse fault. The behavior of this profile is good matching to the behavior of the gravity profile G5 mentioned by Mutib et al. (2019) (Figure 16).
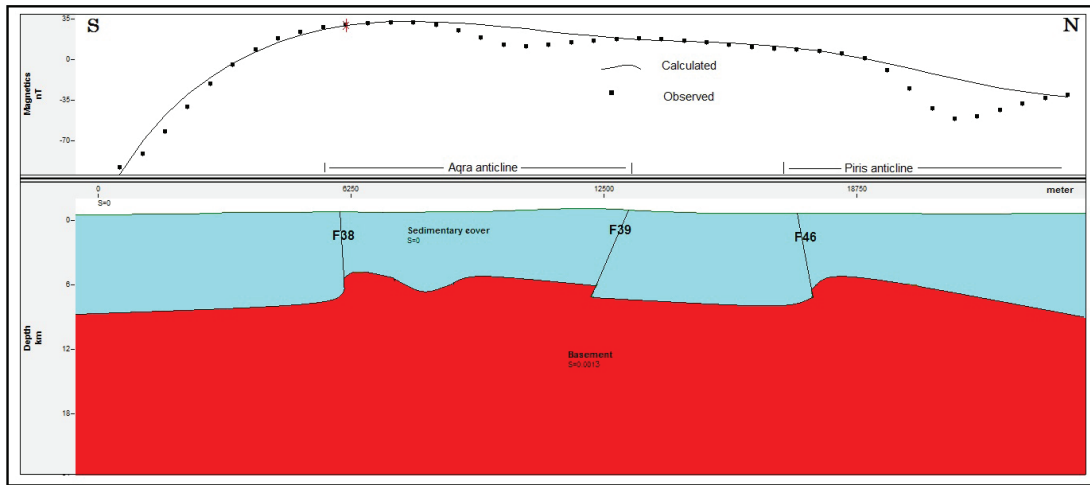
Figure 15. Cross-section and magnetic data along profile Tr5.

Şekil 15. *Tr5 profili boyunca enine kesit ve manyetik veri.*
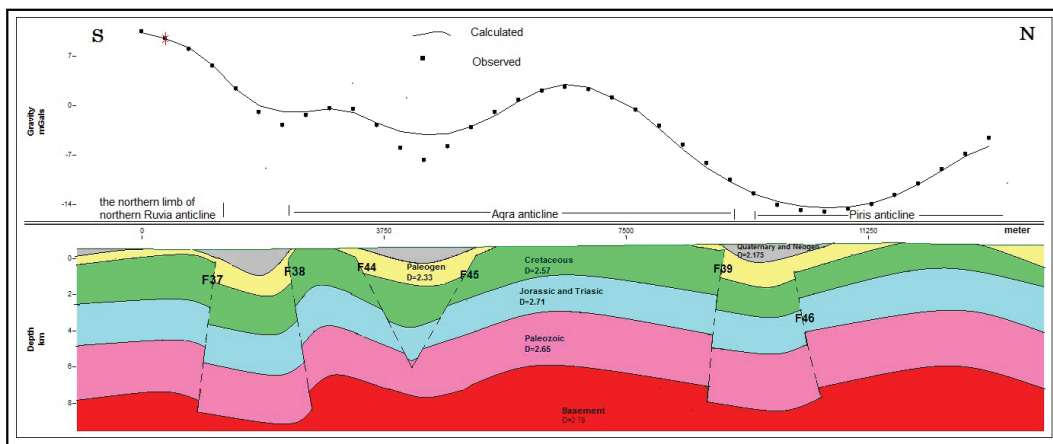

Figure 16. CFigure 16. Cross-section over gravity data along profile G5 (Al-Majid, 2013).

Şekil 16. *G5 profili boyunca gravite verileri üzerinden enine kesit (Al-Majid, 2013).*

DISCUSSION

The studied area locates within the folded zone of northern Iraq comprising parts of high and low folded zones, and the subsurface setting is controlled by a set of subsurface faults and tectonic movements affecting the area through its geological history. In the given circumstances of the studied area where the absence of local or regional seismic profiles except Bashiqa, Kand

and Shaikhan anticlines and the absence of deep bore holes; it seemed that regionally and locally dedicated magnetic surveys would provide an answer to derive the architectural style of the basement complex surface and the overlying structures in the study area.

The empirical formula of Zeng et al. (2007) was applied to isolate the anomalies into their regional and residual, and then a new empirical

upward continuation technique has been used as an effective resolution powers. The optimum upward continuation heights produced by this approach were approximately agreed with the basement depths proposed from previous controlled studies.

The potential field anomalies in the studied area reflect all the contributions of the lateral variations of sedimentary cover due to the tectonic development. Nevertheless, the structural features (folds & faults) were well identified according to the information concluded from and some local geophysical studies (Ghaib, 2001; Kent, 2010; Gulf Keystone, 2010; Almajid, 2013; Mutib et al., 2019).

Using the GM-SYS software, the thicknesses of the litho-facies which adopted in all five magnetic models were taken from the typical locations pointed out from Al-Brifkani (2008), and the Shaikhan bore holes referred by Gulf Keystone (2010). The residual anomalies of the magnetic profiles were interpreted as a reflection of local structures and depressions within the basement and sedimentary cover.

The present study is matching with the results of the previous information which had been concluded from Ditmar et al. (1971) and Mutib and Abdulrahman (2012) who concluded that there are horst and graben features on the basement rocks surface in adjacent areas affected on the overlying sedimentary cover and causing faults and folds.

CONCLUSIONS

1. In the current research it turned out that the best separation between the regional and residual anomalies was achieved using a new empirical upward continuation route pointed out from Zeng et al. (2007). The optimum upward continuation heights applied to the magnetic profiles are ranging between 6 and 8 km under the datum plane reflecting the basement undulations in the study area.

2. The presence of major reverse faults is increasing towards the northeastern parts while normal faults is kept away from the collision boundaries of Arabian plate which thought to be as a result of a differentiation in the compression energy that leads to the most striking distortion and complicated tectonic elements.

GENİŞLETİLMİŞ ÖZET

Jeomanyetik yöntem genellikle hidrokarbon kaynaklarının birikiminde çok önemli olan tortul havzaların oluşumunu yansıtan temel kompleks yüzeyinin yapısal özelliklerini ortaya koymak için bir araştırma yöntemi olarak kullanılır. Jeomanyetik yöntem matematiksel ifadeleri, dipolar özelliklerin manyetik vektör elemanlarının çeşitliliği ve geniş manyetik duyarlılık aralığı nedeniyle diğer potansiyel alan yaklaşımlardan daha karmaşıktır.

Çalışılan alan Kuzey Irak'ta 42˚36'E - 43˚34' E boylamları ve 36˚51'N - 37˚14'N enlemleri ile sınırlanmış, ön ülke kıvrım kuşağı alanıdır. Çok sayıda alçak ve yüksek dağ (Kand, Dahkan, Alqush, Shaikhan, Duhok, Bekher, Atrush, Birifka, Chia Gara, Maten, Aqra, Piris ve Barat) içermektedir (Şekil 1). Manyetik istasyonlar, (Bekher, Shaikhan, Aqra, Piris) birçok antiklinali kesecek şekilde seçilmiştir.

Saha araştırmasını kolaylaştırmak, maliyetleri en aza indirmek ve saha çalışmalarını hızlandırmak amacıyla, jeomanyetik ölçüm aralıkları dizayn edilmiştir. Çalışmada, Proton manyetometresi 250 cm sensör yüksekliğinde kullanılarak yer manyetik alan ölçümleri gerçekleştirilmiş ve verilerden günlük değişimin etkileri giderilmiştir (Şekil 2). Verilere ayrıca, Uluslararası Jeomanyetik Referans Alanı (IGRF) düzeltmeleri uygulanmıştır. Bu düzeltmeler yayınlanan haritalardan ve tablolardan veya belirli bir siteden (www.ngdc.noaa.gov/geomag/

calculators) uygulanabilir. 500 ile 5000 m arasında değişen örnekleme aralıklarıyla belirlenmiş istasyonların koordinasyonları ve rakımları kaydedilmiş ve profillerin uzunlukları sayısal yükseklik modeli (DEM) kullanılarak belirlenmiştir.

Bu çalışmada, optimum yukarı analitik uzanım seviyesinin belirlenebilmesi için iki ardışık yükseklikte yukarı doğru uzanım ile maksimum sapmayı veren yükseklik arasındaki korelasyon katsayısı hesaplaması (r) yöntemi kullanılmıştır (Şekil 3).

Bu çalışma üç adımda gerçekleştirilmiştir. Nicel yorumlamadaki ilk adım, anomaliyi geçen profili seçmek için istasyon yerlerinin görsel olarak incelenmesidir. İkincisi, jeolojik bir önbilgi kullanarak (kuyu logu, sismik kesitler, önceki gravite çalışmaları gibi) hedefin yatay uzantısının, derinliğinin, şeklinin ve kalınlığının tahminidir (Al-brifkani, 2008; Kent, 2010; Gulf Keystone, 2010). Üçüncüsü ise, yukarıda belirtilen tahminleri karşılayan ve son bilgisayar programlarını kullanarak jeolojik yapı ile uyumlu geometrik bir yeraltı modeli oluşturmaktır (Geosoft, 2008). Modelleme çalışması düz profiller gerektirdiğinden (Geosoft programına göre) dolayı, bu düz yüzey üzerine dik olarak yansıtılan tüm manyetik ölçüm istasyonları kullanılarak her bir inceleme hattı için bir referans gridi uygulanmış ve mesafeler her zaman her birimin en güneyindeki ilk istasyondan hesaplanmıştır.

İlk model, Bashiqa ve Kand antiklinallerini oluşturan fayları Şekil 4'te gösterildiği gibi tanımlayan ve sismik bilgileri kullanarak (Kent, 2010) Bashiqa - Kand traversi boyunca yapılmıştır. İkincisi, Shaikhan antiklinal hattı ve iki ters fay boyunca geçerek (Şekil 5) ve Gulf Keyston (2010)'un sismik bilgilerine bağlı olarak açıklanmıştır. Ayrıca, bu modellerin oluşturulması aşamasında önceki tüm gravite, litostratigrafik ve yapısal çalışmalar da dikkate alınmıştır. Tr1, Tr2 ve Tr3 profillerinin istenen modelini oluşturmak

için üç katman için üç manyetik duyarlılık değeri (temel kayalar, Gercus formasyonu olmayan tortul örtü ve Gercus formasyonu) kullanılmıştır. Buna karşılık, Tr4 ve Tr5 profillerinin modelleri, temel kayalar ve bunları örten tortul örtülerini tanımak için (temel kayaçlar ve Gercus formasyonu olmayan tortul örtü) iki katman için iki manyetik duyarlılık değeri olarak belirlenmiştir. Çalışma modellerinde temel kayalar ile sedimanter örtüler arasında 0.0013 emu/cc değerinde manyetik duyarlılık farkı, Gercus formasyonu ile etrafındaki kayaçlar arasında ise 0.0001 emu/cc duyarlılık farkı, kullanılmıştır (Al-Shaikh vd., 1997). Normal manyetik alan T, sapma açısı D ve eğim açısı I, sırasıyla 47000 nT, 5˚, 55˚ olacak şekilde IGRF programından elde edilmiştir. Rezidüel etkiler yukarı doğru analitik uzanımla ilgili geliştirilen bir ampirik yaklaşımla belirlenmiştir (Zeng, vd., 2007). Daha sonra, çalışma alanı için beş rezidüel manyetik profil modeli elde etmek için elde edilen optimum yukarı analitik uzanım seviyeleri kullanılmıştır. Tablo 2, rezidüel manyetik profilleri elde etmek için uygulanan optimum yukarı analitik uzanım seviyelerini göstermektedir ve Şekil 6'da ise manyetik profillerin yerleri belirtilmiştir.

Şekil 7'de gösterilen Tr1 profili yaklaşık 20 km uzunluğundadır ve Bekho antiklinalinin üzerinde bulunan bir negatif anomali gösterdiği Zakho şehri yakınındaki Bekher antiklinali boyunca uzanmaktadır. Bu profil anomalisinin genliği ve yarım genişliği sırasıyla yaklaşık 32 nT ve 3 km'dir. Bu manyetik profilin, Al-Majid, (2013) tarafından oluşturulan gravite profili (G1; Şekil 8) ile karşılaştırılmasıyla, mevcut anomali, iki adet D-B normal fay olarak açıklanmaktadır.

Şekil 9, Bekher antiklinalinin içinden geçen ve belirtildiği gibi bu yapının üzerinde bulunan ve yaklaşık 13 nT ve 2 km yarı genişliğinde bir genliğe sahip pozitif bir anomaliyi ve profil Tr2 uzantısını (10.5 km) göstermektedir. Bu model Al-Majid (2013) (Şekil 10)'dan türetilen gravite profili G2 (Tr2'ye yakın) ile korele edilmiştir ve birtakım KB-GD ters faylarla birlikte bir horst olarak önerilebilir.

Şekil 11'de çizilen Tr3 profili, Bekher ve ChiaGara antiklinallerinin dalımlarını da keserek yaklaşık 12 km boyunca uzanır. Biri Bekher antiklinalinin kuzey ucunda sırasıyla yaklaşık 10 nT ve 3,5 km genliğinde ve yarı genişliğinde ve diğeri de ChiaGara antiklinalinin üzerine yerleştirilmiş iki pozitif anomaliyi göstermektedir. Bu model, Al-Majid (2013; Şekil 12) tarafından elden edilen G3 gravite profiline en uygun şekilde türetilmiştir.

Tr4 profili, Shaikhan antiklinali boyunca yaklaşık 23 km uzunluğunda uzanır (Şekil 13) ve bu yapının üzerinde yaklaşık 5 nT ve 7 km genişliğinde bir pozitif anomali göstermektedir. Şekil 5'de gösterilen sismik kesite ve Al-Majid (2013) tarafından üretilen G4 gravite profiline bağlı olarak simüle edilmiştir (Şekil 14). Gercus formasyonunun manyetik etkileri, diğer profillere kıyasla çok daha az kalın olduğundan dolayı bu profilde görülmemiştir.

Tr5 profili, Aqra antiklinaline ve Piris antiklinallerinin güneyine (Şekil 15), pozitif ve negatif anomaliler olacak şekilde yaklaşık 23 km boyunca uzanır. İlk pozitif anomali, yaklaşık 20 nT genlik ve yaklaşık 4 km yarım genişlikte Aqra antiklinalinin üzerinde belirlenmiştir. Bu anomali iki D-B ters fay tarafından sınırlanan ve daha sonra iki D-B normal fay tarafından kesilmiş bir horst olarak yorumlanabilir. İkincisi, Piris antiklinalinin güney kolunda, yaklaşık 30 nT genliğinde ve yaklaşık 4 km yarım genişliğinde ve bir D-B ters fay ile ortaya çıkmıştır. Bu profili, Mutib ve diğerleri, 2019 tarafından önerilen G5 gravite profilinin modeline oldukça uymaktadır (Şekil 16).

Zeng vd. (2007)'nin ampirik formülü, anomalilerin rejyonal ve rezidüel etkilerini ortaya koymak için uygulanmıştır. Bu yaklaşımla belirlenen optimum yukarı analitik uzanım seviyelerinin belirlenmesinde önceki çalışmalarda önerilen temel derinliği bilgilerinden de faydalanılmıştır.

Çalışılan alandaki potansiyel alan anomalileri, tektonik gelişim nedeniyle tortul örtünün yanal çeşitlemelerinin tüm katkılarını yansıtmaktadır. Bununla birlikte, yapısal özellikler (kıvrımlar ve faylar), elde edilen bilgilere ve bazı yerel jeofizik çalışmalara göre iyi tanımlanmıştır (Ghaib, 2001; Kent, 2010; Gulf Keystone, 2010; Almajid, 2013; Mutib vd., 2019).

GM-SYS yazılımı kullanılarak, beş manyetik modelin hepsinde belirlenen lito-fasiyes kalınlıkları, Al-Brifkani (2008)'de işaret edilen yerlerden ve Gulf Keystone (2010) tarafından belirtilen Shaikhan sondaj kuyularından alınmıştır. Manyetik profillerin rezidüel anomalileri, temel kayaları ve tortul örtü içindeki yerel yapıların ve çöküntülerin bir yansıması olarak yorumlanmıştır.

Bu çalışma, Ditmar ve ark. (1971) ve Mutib ve Abdulrahman, (2012)'ın temel kayalar üzerinde horst ve graben özelliklerinin oluştuğu ve bunun üzerleyen sedimenter kayalarda kıvrım ve faylara neden olduğu sonuçları ile uyumludur.

Mevcut araştırmada, rejyonal ve rezidüel anomaliler arasındaki en iyi ayrımın, Zeng vd. (2007)'nin önerdiği teknik ile elde edildiği sonucunu ortaya çıkarmıştır. Manyetik profillere uygulanan optimum yukarı analitik uzanım seviyeleri, çalışma alanındaki temel ondülasyonunu yansıtan referans düzleminin altında 6 ila 8 km arasında değişmektedir.

Ana ters fayların varlığı kuzeydoğu bölgelerine doğru artmakta, normal faylar ise çalışma alanının kuzeydoğusuna doğru en çarpıcı distorsiyon ve karmaşık tektonik elementlere yol açan sıkıştırma enerjisinde farklılaşma olarak sonuçlanan Arap plakasının çarpışma sınırlarından uzak kalmaktadır.

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