Potential field survey of subsurface structures of the NW segment of the Zagros Fold-Thrust Belt, Kurdistan Region

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Abstract
This study reports results of gravity and magnetic surveys conducted for the first time in the western segment of the Zagros Fold-and-Thrust Belt in the Kurdistan Region. This study attempts to delineate deep structures in an area, which has not been surveyed before. CG-5 Autograv gravimeter and G-857 portable proton-precession magnetometer were used to acquire gravity and magnetic data from 750 stations along over eleven traverses across and parallel to the Zagros trend (NW–SE). Six of these traverses are parallel to the Zagros trend, whereas the others are perpendicular to the trend of the other traverses and can be tied where they intersect. The total length of the traverses is about 1000 km. Tilt Angle of horizontal gradient method is used to detect regional gravity and magnetic lineaments. The mapped lineaments from regional gravity and magnetic surveys are divided into two categories: the NE–SW lineaments, which represent transversal faults in the study area, and the NW–SE lineaments, which represent the Zagros Thrust Faults, some of which may be linked to the inverted basement normal faults of Arabian passive margin (the NW–SE Najd Fault system). The results show that there is a relationship between the regional gravity and magnetic lineaments outlining the same deep geological features. The data presented here confirm the presence of regional longitudinal and transversal lineaments documented in other studies (e.g. Anah-Qalat Dizeh Fault, Surdash-Tikrit Fault, Sirwan Fault, Khanaqin Fault, Zagros Mountain Front Fault, Baranan Back Thrust Fault and High Zagros Reverse Fault) and outlines new lineaments not mapped before. Most of the detected regional lineaments in the current study coincide with the previously confirmed lineaments, which have played a significant role in the tectonic evolution of the Zagros Fold-and-Thrust Belt. As such, this study contributes to a better understanding of the subsurface structure of the Kurdistan segment of the Zagros Fold-and-Thrust Belt and probably the rest of the belt.

KEYWORDS
Kurdistan Region, lineaments, NW Zagros, potential field methods

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INTRODUCTION

Potential field methods detect very small changes in magnetic and gravitational force fields (Reynolds, 1997). They have broad applications on sizes ranging from submeter to global (Hinze et al., 2013). Gravity and magnetic methods have been employed to identify the tectonic structure of basement and sedimentary cover (Benson & Floyd, 2000; Essa et al., 2018), fault parameters (Essa et al., 2021), as well as tectonic boundaries (White et al., 2005). Potential field data are useful in finding structures that are difficult to detect seismically, such as strike-slip faults, regional discontinuities, dykes and basement-cover boundary (Ali et al., 2017).

Most parts of Iraqi territory are covered by gravity and magnetic surveys, with the exception of the Kurdistan Region, where the study area is located (Smith et al., 2011) (Figure 1a). The results of the gravity surveys in the rest of Iraq were compiled and unified by Iraq Geological Survey (GEOSURV) (Jassim & Goff, 2006). The aeromagnetic maps of Iraq were constructed by a national airborne survey flown by Compagnie Generale de Geophysique French team in 1974 (Mousa et al., 2017). Those older gravity and aeromagnetic maps were later reprocessed by Getech group (Fairhead et al., 2012). The regional tectonic frameworks of Iraq, as well as the depth and composition of the basement, are largely determined using potential field data. Longitudinal and transverse fault systems in Iraq were primarily determined using the total horizontal derivative of gravity, which were integrated with magnetic data and satellite images (Jassim & Goff, 2006).

The study area is located in the Kurdistan Region and extends from latitude 34.7 to 36.2°N and longitude 44.4 to 46.1°E (Figure 1b). It covers about 16,000 km² with elevations ranging between about 300 and 2000 m above sea level. In this study, we try to delineate the subsurface tectonic framework of an area in the Kurdistan Region through gravity and magnetic surveys and to fill a gap in the Bouguer gravity and total magnetic map of Iraq. The outcome of this study contributes to a better understanding of the subsurface structures of the area and its neighbouring regions.

GEOLOGICAL SETTING

The northwestern segment of the Zagros Fold-and-Thrust Belt of the Kurdistan Region is located in the northeastern part of the Arabian Plate (Lawa et al., 2013). The belt is a part of the Alpine-Himalayan Mountain Chain, which extends from the Oman Line in SE Iran for 2000 km along strike to the NW, across the Kurdistan Region, to the East Anatolian Fault in southeastern Turkey (Figure 2a). The orogen is caused by the convergence of the Arabian and Eurasian plates when the Neo-Tethys Ocean closed (e.g. Agard et al., 2005; Al-Qayim et al., 2012; Beydoun et al., 1992). The time of the collision of the Arabian and Eurasian plates is still controversial; however, there are two main perspectives. According to some studies (e.g. Alavi, 1994, 2004), the collision started in the Late Cretaceous, whereas other studies (e.g. Agard et al., 2005; Gholami Zadeh et al., 2017) contend that it began in the Late Eocene–Oligocene.

Three major fault systems have been documented in Iraq: N–S Nabitate system, NW–SE (Zagros trend) and NE–SW transversal system. However, only the latter two is shown in the study area (Figure 2b). Except for the faults formed and/or reactivated during the Zagros orogeny, many of the faults in these systems are believed to be formed during the Late Proterozoic Pan-African Orogeny (900–610 Ma) (Jassim & Goff, 2006) and were periodically reactivated over different times in the Phanerozoic, regulating the distribution of minor structural highs and lows that controlled subsidence and facies patterns (e.g. Hessami et al., 2001; Jassim & Goff, 2006). The fault systems divided the study area into a number of longitudinal and transverse blocks. In this study, the nomenclatures of the longitudinal zones and bounds proposed by Al-Qayim et al. (2012) are followed.

According to Jassim and Goff (2006), the NW segment of the Zagros Fold-and-Thrust Belt in the study area is categorized into five main NW–SE-trending longitudinal tectonic zones: Shlair Zone; Zagros Suture Zone (ZSZ); Zagros Imbricate Zone (ZIZ); Zagros High Folded Zone (ZHFZ) and Zagros Low Folded Zone (ZLFZ) as well as three transversal blocks from the NW to SE: Deir Al Zor-Erbil block; Kirkuk embayment and Mesopotamian block (Figure 2b).

The longitudinal zones are defined by major longitudinal faults, including the Zagros Thrust Fault, separates the ZSZ from the ZIZ; the High Zagros Reverse Fault, separates the ZIZ from the ZHFZ; and the Zagros Mountain Front Fault, separates the ZHFZ from the ZLFZ (Figure 2b) (Al-Qayim et al., 2012; Jassim & Goff, 2006; Lawa et al., 2013). These major zone-bounding thrust faults which run parallel to the Zagros trend formed as a result of the closing of the Neo-Tethys Ocean between the Arabian and Eurasian Plates (Talbot & Alavi, 1996), and they are thought to represent surface manifestations of reactivated basement faults of the NW–SE Najd Fault system (Ameen, 1992; Jassim & Goff, 2006).

The transversal blocks are separated by NE–SW transversal faults. This fault system may have developed in Late Pre cambrian and may represent a conjugate trend of to the Najd Fault system (Jassim & Goff, 2006). The transversal fault system was active during opening of the Neo-Tethyan Ocean in Permian and Triassic times and later reactivated in Late Jurassic, leading to the formation of transversal blocks (Jassim & Goff, 2006). Anah-Qalat Dizeh Fault separates Deir Al Zor-Erbil block from the Kirkuk embayment, whereas the
Sirwan Fault (SF) separates the Kirkuk embayment from the Mesopotamian block. The Kirkuk embayment, which spans between the Anah-Qalat Dizeh Fault in the northwest and the SF in the southeast, is the most important and broadest transverse block that encompasses the most of the study area.

The study area is characterized by numerous folds whose axes trend NW–SE parallel to the Zagros trend (Figure 2b). The folds have variable hinge lengths, amplitudes, wavelengths and style of folding which may be due to lateral facies change, thickness variation and the fault distributions. Folds are segmented into separate domes, and their fold axes are bent at the intersections with transversal faults. Folds are doubly plunging in an en-echelon pattern and often fault-cored, with dominating foreland and hinterland verging thrusts (Farzipour-Saein & Koyi, 2014; Jassim & Goff, 2006; Koyi et al., 2004; Mobasher, 2007).

The Phanerozoic sedimentary cover has been classified into autochthonous and allochthonous units. Autochthonous
units cover the vast majority of the study area. The Kurdistan foreland basin (Lawa et al., 2013) has been an area for the deposition of thick sequences of marine and continental autochthonous facies. This sedimentary succession is classified into a number of mega-sequences and interrupted by many sedimentary gaps from the opening of the Neo-Tethys until the last phase of the Arabian–Eurasian collision (Jassim & Goff, 2006; Lawa et al., 2013; Le Garzic et al., 2019). The Infra-Cambrian, Paleozoic and Mesozoic mega-sequences were deposited on the passive margin of the Arabian Plate, whereas the Cenozoic mega-sequences were deposited during the Alpine orogeny (Jassim & Goff, 2006). The surface geology of the study area is dominated by a wide range of rock types of different lithologies and ages. The exposed formations range in age from the Early Jurassic to the Holocene formations. The oldest formations, the Early Jurassic

Formation, can be seen in the core of the Surdash anticline, the Piramagroon anticline and the Saidsadiq district.

FIELD WORK AND METHODOLOGY

In the present study, the CG-5 Autograv gravimeter and G-857 portable proton-precession magnetometer were used to collect gravity and magnetic data. Their resolutions are of the order of 1 μGal and 0.1 nT, respectively. For each station, the longitude, latitude and elevation were determined using the Garmin GPS72 which has a 3-m accuracy. The essential step in gravity and magnetic survey is the design of the stations. The survey is a ground surface survey that was carried out for the first time by taking measurements in 750 stations (Figure 1b). Before taking gravity measurements, almost 4 min were spent for gravimeter stabilization at each station. The raw gravity data were recorded three times at each station, and the value with low standard deviation is selected. The interval between the start of the three consecutive readings was around 5 s. On the other hand, the magnetic data measurements were conducted on days with no magnetic storms. In each station, at least three magnetic readings were taken at the same position, and their average was computed. During the survey, gravity and magnetic data were collected 300–400 m away from power lines, several metres away from ferrous materials and without wearing any metallic objects (details of the data observations are provided in Appendix A). For the sake of accuracy and quality control, 10% of the total gravity measurements were repeated at the same day, as repeated stations, and 3% of them were repeated at different days, as control stations. Based on the repeated observations, the final accuracy of the gravity measurements is ±0.04 mGal.

Gravity and magnetic data were taken at the same sites along 11 traverses whose spacing is not equal because of the vast survey area, variations in topography, limited road access and the prevalence of mines in certain areas. The data were collected in two periods. The first period began on October 25, 2019 and finished on July 11, 2020. Measurements were performed along six traverses that cut across the transversal fault systems and run approximately parallel to the Zagros trend (NW–SE) (Figure 1b). The station spacing was around 1 km, and there were 675 stations in total. The final stage of measurements was completed between January 6 and February 7, 2021. During this stage, measurements were taken along five traverses perpendicular to the former ones (i.e. NW–SE). Station spacing of these measurements was 3 km, with 75 stations in total. This step was taken in order to achieve the best possible outcome, minimize ambiguity and tie the data to those from the longitudinal traverses (Figure 1b).

The study area has not been surveyed before. The few base stations in the area are mainly used to determine drift and diurnal corrections. Accordingly, multiple base stations and base network had to be established before conducting the gravity survey (Figure 1b). There is only one international reference gravity base station in the survey area, which has an absolute gravity of 979,495.1 mGal. This base station was used to establish five primary and four secondary base stations (Table 1). ABABA-type loop after applying drift correction is a typical technique for transferring or tying the gravity base stations. As the measurements were taken on long traverses, the travelling base station method was also used to establish several local gravity and magnetic base stations during the survey (details of procedures to establish base stations are provided in Appendix A).

DATA PROCESSING

Gravity and magnetic measurements are significantly affected by a broad range of terrain, surface, geological, instrumental and planetary sources which commonly mask or distort the anomalies of interest (Blakey, 1996), and these effects were removed from the collected raw data to obtain anomalies directly connected to geological sources.

Gravity data processing

In order to obtain the complete Bouguer gravity (Figure 3), these corrections were employed: calibration factor (C.F.), tidal and drift correction, latitude correction, atmospheric mass correction, free air correction (FAC), Bouguer spherical cap correction and terrain correction. C.F. was measured by taking measurements at two base stations with defined absolute gravity values using an ABABA-type loop. The C.F. used in the data processing was 0.99254758. The raw data are then multiplied by the C.F. value to obtain the observed gravity. The CG-5 gravimeter software automatically removed the tidal effects from the observed gravity by entering in the latitude, longitude and difference between the gravimeter clock time and GMT. The earth tide corrections were removed from the observed gravity which ranges from 0.01 to 0.3 mGal. Instrumental drift, on the other hand, was assessed by adjusting several base stations and repeating measurements on them every 3–4 h on average. Observed gravity values were corrected by adding or subtracting the drift value from the observed gravity values. The average gravimeter drift value for whole survey was 0.037 mGal.

The latitude correction was made by subtracting the theoretical gravity from the observed value. The Somigliana closed-form formula (Moritz, 1980) based on the 1980 Geodetic Reference System (GRS80) was used to calculate the theoretical gravity. The effect of atmospheric mass was removed from the theoretical gravity using the Wenzel (1985)
The stations have different elevations ranging from 400 to 2000 m above sea level. Thus, FAC was applied to account for the decrease in gravity with increasing height above sea level resulting from increased distance from the centre of the Earth. The frequently used expanded version of the FAC, in mGal, based on the GRSS80 ellipsoid (Hinze et al., 2013), was used to calculate FAC, which takes into account the effect of latitude and height above sea level at the same location. The corrections were then added for gravity stations because they are located above sea level. The Bouguer spherical cap correction was used to exclude the effect of rocks between the observation points and the reference datum as well as the curvature of the Earth from the records. The LaFehr (1991) closed-form formula was used for the spherical cap of a radius 166.7 km. The correction values were subtracted from the theoretical gravity because the stations are above sea level.

Terrain correction was numerically computed using the Geosoft Oasis Montaj software, which was based on combination algorithms of Nagy (1966) and Kane (1962). The software requires the digital elevation models (DEMs) of the study area and its surroundings (Figure 5) to calculate the average elevation of each prism in relation to the height of the measurement point. Resolution of the DEM is 12.5 m × 12.5 m which was employed to calculate terrain impacts accurately. The contribution of topography over the stations was determined up to a distance of 22 km, beyond which their impacts were minimal. The topographic effects range from 0.1 mGal in flat areas to 15 mGal in mountainous regions which were subsequently added to the observed gravity. The terrain correction was added to the simple Bouguer gravity to produce a quantity complete Bouguer gravity. Determination of densities for the aforementioned corrections will be explained later (and in Appendix B). The mean sea level was used as datum in the corrections. The final estimation of the error in the gravity anomaly computation is explained in Appendix C.

### Magnetic data processing

The magnetic data measurements were conducted on days with no magnetic storms; based on magnetic storm prediction websites. The raw magnetic data were subjected to diurnal and geomagnetic corrections. Many base stations were used to monitor the diurnal fluctuations throughout the survey day to determine the diurnal corrections. As only one magnetometer was utilized to collect data, it returns to a base station were spaced out across a period of 2–3 h on average. Magnetic raw data can be corrected by adding or subtracting the diurnal correction from the magnetic raw data. The diurnal fluctuations varied from 4 to 10 nT throughout the whole studied area, with an average value of roughly 7 nT.

The magnetic field strength of the Earth changes with latitude thus the geomagnetic correction was used to eliminate this effect. Magnetic field strength in the study area ranges from 47,945 to 47,495 nT. The geomagnetic correction was calculated using the latest version, 13th generation, of the International Geomagnetic Reference Field formula (IGRF-13), and theoretical field (https://www.ngdc.noaa.gov/geomag/calculators/magcalc.shtml?useFullSite=true#igrfwmm). The IGRF calculation depends on the latitude, longitude and elevation of the stations. Magnetic data at any given location were obtained by subtracting the theoretical field (IGRF-13) value from the diurnal corrected magnetic value.

Following Baranov (1957), the total magnetic intensity data (Figure 4a) were reduced to the magnetic pole (RTP) (Figure 4b). The geomagnetic field considered in the RTP computation had a mean declination of around 5.2°, whereas the inclination had a mean value of 54.2° and ranges by around
The mean density of the exposed formations/units was determined from laboratory measurements on collected samples, density logs and previous studies (details about density determination are provided in Appendix B). The magnetic susceptibility of the exposed rocks, on the other hand, was determined using a magnetic susceptibility metre (SM-30). Because sedimentary rocks occupy virtually all of the study area, the measured magnetic susceptibility of the rocks is very low and therefore neglected.

One of the major issues in gravity data processing is determining which density to be used in the corrections. According
to Hinze et al. (2013), the use of variable densities is especially important where actual densities vary significantly from the average value used in calculating the mass correction and in regions of rugged topography. However, variable densities in the mass correction are not necessary where modelling of anomalies directly incorporates variable densities. Additionally, Lowrie (2020) stated that the density of rocks in the vicinity of a gravity profile is important for the calculation of the Bouguer plate and terrain corrections. Nettleton (1939) method has been tested in other studies to find the density of formations which can be used later in the gravity corrections. However, this method was not applicable to our area due to lack of the conditions required to apply the method and vast survey area.

The average density of 2.17 g/cm$^3$ had been utilized in gravity reduction for most Iraqi territories. However, in the survey area, actual densities vary greatly from the mean value due to the extent of large area, large topographic variation.
FIGURE 5 Digital elevation models (DEM) of the study area with traverse tracks (labelled A–K). The traverses have their own densities, which was estimated on a station-by-station basis across a 22 km distance. Traverse-A has variable density (2.49–2.69 g/cm$^3$), Traverse-B has 2.44 g/cm$^3$, Traverse-C has 2.39 g/cm$^3$, Traverses-D–F have 2.32 g/cm$^3$, and the other traverses have variable densities.

and different lithologies. As a result, two groups of densities were used in the corrections in this study. One of them, which was determined based on geological and geophysical information available in Iraq, was a single average density of 2.61 g/cm$^3$ for the sedimentary cover (Al-Banna & Al-Heety, 1994). The other group of mean density was a variable density, which was estimated on a station-by-station basis across a 22 km distance. The average density of the exposed formations within a radius of 22 km distance from each station has been calculated. Based on this approach, all stations along each longitudinal traverse have nearly the same density value, even though the longitudinal traverses have variable densities (Figure 5) (details are provided in Appendix B).

Two complete Bouguer gravity maps were created for the area based on the standard density (2.61 g/cm$^3$) and variable station-to-station density (Figure 3a,b). Both maps match well in terms of the shape, sharpness and amplitude of the anomalies; however, as expected, they differ mainly in gravity values. The created Bouguer gravity map based on the variable density (Figure 3a) is thought to be the best reflection of the variation in subsurface density of the study area due to two main reasons. First, the actual densities of the exposed formations in the study area differ significantly from the mean density value used for most Iraqi territories because the current survey was carried out over a large area (16,000 km$^2$) with a wide range of topographic variations and exposed lithologies, resulting in different densities around the observation stations. Second, the surveyed area, which is part of the Zagros orogeny, is composed of many tectonic zones that run NW–SE (Zagros Low Folded Zone, Zagros High Folded zone, Zagros Imbricated zone etc.) and have an impact on the variations in density distribution (Figure 5). Therefore, our interpretation is solely based on the variable density data.

Almost all longitudinal traverses extending NW–SE (Traverses B–F), except Traverse-A, have their own densities that do not change along the traverse because they are parallel to the general strike of Zagros orogeny. However, the NE–SW-trending traverses (Traverses G–K), which are perpendicular to the former traverses, have variable densities from NE to SW direction (Figure 5). The density of the formations on the perpendicular traverses is based on their positions between the longitudinal traverses (details are provided in Appendix B).
METHODOLOGY

Regional–residual separation

Generally, measured gravity and magnetic fields are the result of a superposition of anomalies from various sources; deep and shallow sources (Reynolds, 1997). Different approaches have been proposed to separate regional and residual anomalies starting from graphical to analytical methods. However, there are several methods to separate regional and residual anomalies but none of them provide fully satisfactory results because they depend on several factors, such as the interpreter experience, mathematical factors and geological factors (Arora et al., 2011). For this study, the separation of regional from residual anomalies by graphical methods was difficult and neglected as the regional field in the study area was more complicated. Additionally, a trend surface analysis is not applicable as it is considered that the magnetic susceptibilities and density contrast over these long traverses, 150 km long on average, are not uniform. Therefore, the upward continuation (UPC) filter (Jacobsen, 1987) was employed in this study to separate regional gravity/magnetic anomalies.

The main problem in the application of UPC method was the selection of appropriate height of the UPC. The selection on the optimal height varies according to the type of the anomalies. This problem was addressed by the use of an empirical technique presented by Zeng et al. (2007). The method is dependent on the series of cross-correlation between UPC s at two successive heights, over a range from 2 to 28 km with a height interval of 2 km, versus the height. The maximum deflection of these cross-correlation values from the chord takes place at a height that approximates the optimum height for regional–residual separation. The optimal height for both gravity and magnetic data in the regional–residual separation was 10 km (details are provided in Appendix C). The residual gravity (Figure 3d) was derived by removing regional gravity (Figure 3c) from the complete Bouguer anomaly map (Figure 3a). Additionally, the residual reduced to the magnetic pole (RTP) maps (Figure 4d) were derived by removing the regional RTP (Figure 4c) from the RTP map (Figure 4b).

Edge detection method

There are several edge detection methods for determining lineaments from potential field data, and most of them depend on the vertical or horizontal derivatives of the anomalies, or combinations of them (Pham et al., 2018). Horizontal derivatives are found very useful for determining the boundaries of regional anomaly sources (Hinze et al., 2013). Additionally, Jallouli et al. (2013) used the horizontal gradient magnitude as an edge detector function to highlight an E–W regional gravity trend interpreted as a deep fault in the northern Tunisian Atlas. Abdelfattah et al. (2021) used the same approach to enhance NE–SW gravity trends corresponding to the boundaries of basement blocks with different densities and compositions in the eastern flank of the Red Sea. Total horizontal derivative (THDR) method was previously employed to identify the regional fault trends in Iraq (Jassim & Goff, 2006).

In this study, tilt angle of the horizontal gradient (TAHG) filter (Ferreira et al., 2013) was used to construct regional gravity and magnetic lineaments (Figure 6a,b). Both Bouguer gravity maps (Figure 3a,b) were used to outline the regional gravity lineaments in the study area using TAHG method. The lineaments determined from both Bouguer maps were almost similar (details are provided in Appendix C). However, our interpretation is based on the variable density data. The TAHG method is dependent on the enhancement of the THDR of anomalies using the tilt derivative. The TAHG is defined as the arctangent of the ratio of the vertical derivative of the THDR to the modulus of the THDR (Equation 1).

\[
\text{TAHG} = \tan^{-1}\left(\frac{\frac{\partial \text{THDR}}{\partial z}}{\sqrt{\left(\frac{\partial \text{THDR}}{\partial x}\right)^2 + \left(\frac{\partial \text{THDR}}{\partial y}\right)^2}}\right). \tag{1}
\]

Due to the characteristics of the arctangent, the TAHG transform range is from $-\pi/2$ to $\pi/2$. TAHG anomalies are less dependent on the source depth and equalize amplitude signals from shallow and deep sources. TAHG maximum values are located near the edges, even for deeper sources. The TAHG method is less sensitive to noise than the THDR method. The anomalies in the TAHG map are reflected by sharp continuous peaks, which highlight the structures (Ferreira et al., 2013).

RESULTS

Detected lineaments from gravity and magnetic data are combined to define the lineament system of the study area. As a consequence, two sets of lineaments are extracted: NE–SW and NW–SE-trending lineaments (Figure 7). Around Dokan Lake, five almost NE–SW-trending regional lineaments (L1, L2, L3, L4 and L5) with variable lengths are identified from the gravity and magnetic data (Figure 7). L1, L3 and L4 lineaments are derived from magnetic data, whereas L2 and L5 are determined from the gravity data. According to earthquake data collected by the USGS National Earthquake Information Centre from 1900 to 2021, this area has several earthquake epicentres, indicating that the lineaments are still active today.
Despite the mismatch between the NE segments of the L1 and L2 lineaments, they are believed to be related to the same geological structure, Anah-Qalat Dizeh regional transversal fault (AQDF). Their total lengths are around 38 and 45 km, respectively (Figure 7). The L1 lineament is oriented N45˚E and almost coincides with a lineament labelled the AQDF by Jassim and Goff (2006), whereas the L2 lineament has an ENE trend and nearly coincides with another lineament, which is also labelled AQDF by a different group of researchers (Al-Kadhimi et al., 1996; Stevanovic & Markovic, 2004) (Figure 7). Even though, according to Fouad (2015) and Al-Naqib (1967), the AQDF does not propagate to the study area, and the results of this study confirm its existence (Figure 6). The existence of the fault is displayed morphologically and tectonically; it offsets the Mountain Front Fault (MFF) approximately 7 km left laterally (Figure 7). The AQDF has experienced sinistral strike-slip movement, resulting in at least 2 km of horizontal displacement near Al-Fatha area (i.e. outside of the study area), in the last few million years. Neo-tectonic activity along this fault is also proven by several recorded earthquakes (Aqrawi et al., 2010; Jassim & Goff, 2006).

Lineaments L3, L4 and L5 are determined for the first time and are not reported previously in any tectonic maps of Iraq. The total lengths of L3 and L4 are around 56 and 77 km, respectively. L5 is shown only by the gravity data and extends for about 24 km in ENE direction (Figure 7). It runs parallel to L2 and L6 lineaments. L2 and L5 lineaments bound the Dokan Lake in the NE and SW, respectively.

Lineament L6 is about 64 km long and runs approximately in the ENE direction, as identified only on gravity data (Figure 7). The L6 lineament matches with the Surdash-Tikrit Fault (STF) which was reported by Al-Kadhimi et al. (1996); Stevanovic and Markovic (2004) (Figure 7). This fault displaces the Zagros MFF (ZMFF) about 17 km right laterally (Figure 7). Based on the field observation, dextral strike-slip movement detected along this fault (Al-Hakari, 2011). However, this fault is not reported on the tectonic maps of Iraq (e.g. Fouad, 2015; Jassim & Goff, 2006).

Lineament L7 is a short magnetic lineament with an NNE trend that extends for about 25 km. This lineament may correlate to the NE segment of the Amij-Samarra-Sulaimani Fault (ASSF) reported by Aziz et al. (2001) and Jassim and Goff (2006) (Figure 7). The ASSF might have affected the sedimentary cover in the region where abrupt lateral facies changes and thickness variations between the Early Cretaceous formations (Qamchuqa–Sarmord Formations and the Balambo Formation) have been reported along this fault from the Tithonian to Cenomanian period (Aziz et al., 2001; Jassim & Goff, 2006).

Lineaments L8 and L9 run roughly in the NE–SW direction and are extracted from the gravity and magnetic data, respectively (Figure 7). Their total lengths are about 69 and 79 km, respectively. Both lineaments are identified for the first time.
and are not documented previously in any tectonic maps of Iraq (e.g., Al-Kadhimi et al., 1996; Fouad, 2015; Jassim & Goff, 2006). The L8 lineament is close and parallel to a lineament called Barzinja lineament in this study, not labelled in previous literature, but mapped by Stevanovic and Markovic (2004).

The L9 lineament is almost parallel to the Sirwan River and Sirwan Fault (SF) (Figure 7). Next to the L9, there is L10 lineament which follows the Sirwan river and coincides very well with the SF described by Aqrawi et al. (2010); Jassim and Goff (2006); Lawa and Ghafur (2015) (Figure 7). This reported deep-seated fault has been detected on the regional magnetic data; however, this is not very clear in the gravity data (Figure 7). Despite the shifts between L9 gravity lineament and L10 magnetic lineament, they are most probably related to the same source, SF. In the SE of the study area, there is L11 lineament that has an NNE trend and then its direction changes to NE–SW (Figure 7). Its NNE segment coincides with the Khanaqin Fault. The lineament is derived from the gravity data and extends for about 53 km.
There are seven detected NW–SE-trending regional gravity and/or magnetic lineaments (L12, L13, L14, L15, L16 and L17) with variable lengths in the study area. L12, L14, L16 and L17 lineaments are derived from the gravity data only, and the rest are extracted from the magnetic data. L12 lineament is approximately 90 km long and has WNW direction. The lineament is identified only from the gravity data, and it may represent a major fault which has not been identified in earlier studies. The L12 lineament crosses the High Zagros Reverse Fault (HZRF), Zagros Thrust Fault (ZTF) and STF at different localities.

The large-scale curved lineament L13 almost coincides with the HZRF (Figure 7) which has been reported previously in the tectonic maps of Iraq by Al-Kadhimi et al. (1996) and Jassim and Goff (2006). The HZRF is regarded as an active deep basement fault (Bahroudi & Talbot, 2003; Mobasher, 2007) which separates the Zagros Imbricate Zone from the Zagros High Folded Zone (ZHFZ) (Al-Qayim et al., 2012). The HZRF dips 65°NE and is visible on the surface as an axial fault running along the Balambo and Azmar anticlines (Al-Qayim et al., 2012) (Figure 8). L14 lineament stretches for about 69 km in WNW direction. It is almost parallel to the Baranan Homocline and coincides well with the Baranan Back Thrust Fault (BBTF) (Figure 7) which is reported in previous studies (Al-Hakari, 2011; Stevanovic & Markovic, 2004). The BBTF is reported to be an SW-dipping basement fault which is displayed on the surface as Baranan Homocline verging to the hinterland (Al-Hakari, 2011). The L15 magnetic lineament, which extends in NW–SE direction for about 140 km, runs between and parallel to the BBTF and ZMFF (Figure 7). This lineament is identified for the first time in this study, and it is not reported in any tectonic maps of Iraq (e.g. Al-Kadhimi et al., 1996; Fouad, 2015; Jassim & Goff, 2006). However, its validity is uncertain due to the lack of strong magnetic data signals.

L16 lineament runs for approximately 65 km with an NW–SE direction. It coincides almost with the ZMFF (Figure 7) which is reported in previous studies (Al-Kadhimi et al., 1996; Fouad, 2015; Jassim & Goff, 2006). However, the L16 lineament is shorter than the documented ZMFF. The ZMFF is suggested to be a deep, active blind reverse fault with an NW–SE trend that separates the ZHFZ (hanging wall) from the Zagros Low Folded Zone (footwall) (Al-Qayim et al., 2012). Stratigraphic, seismic and drilling investigations have shown more than 6 km of vertical displacement along the ZMFF (Mobasher, 2007). The Darbandi Bazian-Qaradagh-Sagurma anticline represents the surface expression of the fault in the study area (Al-Qayim et al., 2012) (Figure 8).

L17 lineament runs in NW–SE direction which is parallel and close to the Kirkuk Fault reported by Jassim and Goff (2006). The Kirkuk Fault is considered to be one of the structures of Najd Fault system that is a significant structure in Iraq because it forms boundaries not only of the Precambrian terranes but also of the tectonic zones (Jassim & Goff, 2006). The L17 lineament consists of two segments: one in the NW and the other in the SE. They are believed to form one long lineament. However, their connectivity is poor due to a lack of potential field data in the middle of the area.

**DISCUSSION**

Gravity and magnetic surveys undertaken in this study outline some of the features of the subsurface tectonic framework of a large part of the Kurdistan Region. Based on their magnetic and/or gravity anomalies they produce, there are three groups of lineaments in the area (Figure 7). Gravity-derived lineaments may have their origins in deeper sedimentary column and/or in the crystalline basement, whereas magnetic-derived lineaments may be deep-seated lineaments in the crystalline basement. The lack of exposure of magnetically derived lineaments on gravity data might be due to the uniform lateral density between the formations in the deeper sedimentary column and/or the basement in the region. On the other hand, lineaments depicted on both gravity and magnetic data may indicate that they are deep-seated structures in the basement and deeper units of the sedimentary cover.

The resolution of the data presented here may not precisely depict all the lineaments in the study area. This may be due to the large traverse spacing of this vast survey area which was dictated by variation in topography, limited access and the presence of mines in specific regions. However, despite these limitations, the majority of the derived lineaments depicted in this survey coincide well with the reported lineaments in earlier studies.

In general, regional gravity and magnetic derived lineaments can be correlated, which suggests that they may reflect the same subsurface geological features (Figure 7). However, there is some mismatch between the two types of data which can be due to several reasons. First, they mismatch due to decoupling between cover and basement. The lineaments may be shifted as they propagate upward to the sedimentary cover, which is decoupled from the basement by many decollement units within the cover stratigraphy. In many places, the sedimentary cover of the Zagros Fold-Thrust Belt is decoupled from its underlying crystalline basement by the evaporation of Hormuz Formation (Kent, 1979; O’Brien, 1957). Therefore, the surface expression of the faults may not coincide with the location of the basement faults at depth (Koyi et al., 2016). Second, it has been reported by Ali et al. (2017) that for the basement survey of the United Arab Emirates, gravity response associated with lateral lithological density variation within the sedimentary segment was significantly bigger than gravity response caused by basement surface morphology. In the study area, such lateral density variation in the cover units may cause different
Gravity and magnetic fields reflect physical property variations in distinct ways: Even for simple geologic forms, gravity and magnetic anomalies vary (Cascone et al., 2017). Fourth, magnetic susceptibility and rock density are not directly related: Geologic boundaries which have a density contrast may not necessarily possess magnetic susceptibility contrast, and vice versa. Simple geologic structures may display comparable variations, but geologic province borders are likely to involve complicated changes in structural style and lithology, as well as bulk changes in physical attributes (Cascone et al., 2017). Last, the shift and mismatch between the two anomalies may be due to that contacts and discontinuities are not vertical (Mousa et al., 2017).

Despite some mismatch between the gravity and magnetic anomalies, interpreted lineaments from both gravity and magnetic data are compiled to delineate the lineament system of the study area. Two sets of lineaments are extracted from these data; NE–SW and NW–SE-trending lineaments (Figure 7). The detected dominants of NE–SW-trending anomalies are interpreted to represent the transversal fault system, which they may have developed in Late Precambrian (Jassim & Goff, 2006). The transversal fault system was active during opening of the Neo-Tethyan Ocean in Permian and Triassic times and later reactivated in Late Jurassic, leading to the formation of transversal blocks (Jassim & Goff, 2006).

The presence and alignment of several regional faults in the study area are a matter of debate amongst researchers, as they have been identified in prior studies based essentially on surface geology due to the lack of geophysical data (gravity, magnetic and seismic). For instance, based solely on surface geology, some researchers (e.g. Karim et al., 2016) argued...
agains against the presence of Sirwan deep-seated fault (also called Khabaniqin and/or Darbandikhan Fault) in the southeastern part of the study area. In contrast, others (e.g. Al-Kadhimia et al., 1996; Fouad, 2015; Jassim & Goff, 2006; Lawa & Ghafer, 2015) confirmed its existence based on surface and subsurface data. This NE–SW-trending fault may have controlled the facies patterns and thickness variation in the area (Jassim & Goff, 2006; Lawa & Ghafer, 2015). However, the results from the current study confirm its existence with the same trend mapped by Jassim and Goff (2006) (Figure 7).

The NNE trending part of the L11 lineament almost coincides with the Khabaniqin Fault (KF), as documented by Allen et al. (2004; Bahroudi and Talbot (2003)), although its NE–SW-trending segment does not coincide. This may suggest that the Khabaniqin basement fault has not propagated northerly into the study area but instead may have an NE–SW trend (Figure 8). The abrupt swing in the direction of the KF from NNE to NE–SW may be related to the collision between Arabia and Eurasia. According to Hessami et al. (2001), some of the transversal faults changed their direction during the collision between Arabia and Eurasia.

There is also an obvious relationship between transversal NE–SW-trending lineaments and plunging of several anticlines, which may imply that transversal lineaments play a significant role in controlling along-strike continuation of the anticlines (e.g. the NW and SE plunges of Piramagroon anticline, NW plunge of Azmar anticline, SE plunge of Bna Bawi and Safeen anticlines) (Figure 8).

The two groups of deep-seated lineaments detected by the gravity and magnetic data comprise the main deep-seated structural features that have had a significant impact on depositional evolution of the Zagros basin and its subsequent tectonic evolution. The NW–SE-trending anomalies on both the magnetic and gravity data represent basement normal faults of Arabian passive margin, that is the Najd Fault system, which were inverted during the collision of Arabian Plate with Eurasian plate. It is worth underlining that the spacing of the NW–SE lineaments derived from the regional gravity and regional magnetic data is about 20 km. Normal faults along passive margins exhibit variable spacing (Bell et al., 2014; Osmundsen & Ebbing, 2008; Sapin et al., 2021) possessing different amounts of displacement. The spacing of the NW–SE lineaments outlined by our surveys is expected to represent the distance between these faults after inversion. However, their pre-inversion spacing would be expected to be wider within the range of spacing seen in many current passive margins.

The NE–SW-trending structures which are interpreted to be part of the Pan-Arabian grain show wider spacing (25–50 km) on regional gravity and magnetic data. These lineaments separate major tectonic blocks with different sedimentary settings along the Arabian passive margin and were reactivated during the formation of the Zagros Fold-and-Thrust Belt. These lineaments have resulted in large facies and thickness variations of the sedimentary cover. For instance, the Anah-Qalat-Dizeh fault, which forms the northern limit of the Kirkuk embayment and the southeastern boundary of the Mosul High, produced a graben, outside the study area, where over 2000 m of Upper Cretaceous sediments were deposited; on the adjacent footwall blocks, the Upper Cretaceous section is less than 300 m thick (Jassim & Goff, 2006). The Sirwan Fault (SF) forms the southeastern limit of the Kirkuk embayment and the northern boundary of the Mesopotamian Transversal Block. The Mesopotamian Block contains thick Cretaceous and Palaeogene sequences that thin towards the SF. Two distinct depositional sequences with varying thicknesses evolved on each side of the SF (Lawa & Ghafer, 2015).

CONCLUSIONS

This study presents results of the first gravity and magnetic surveys of the northwestern segment of the Zagros Fold-and-Thrust Belt of the Kurdistan Region. From the collected gravity and magnetic data, the extracted lineaments are classified into two groups based on their orientations: NE–SW- and NW–SE-trending lineaments. The NE–SW-trending lineaments represent transversal faults, and the NW–SE-trending lineaments may represent both Zagros thrusts and inverted basement normal faults of Arabian passive margin. Our results show the following:

- There is a correlation between regional gravity and magnetic derived lineaments which indicate the presence of the same subsurface geological features in the basement and/or deeper sedimentary cover.
- This study confirms the presence of several regional longitudinal and transversal lineaments identified in earlier studies, such as Anah-Qalat-Dizeh fault (AQDF), Surdash-Tikrit Fault (STF), Sirwan Fault (SF), Khabaniqin Fault (KF), Zagros Mountain Front Fault (ZMFF), Baranan Back Thrust Fault (BBTF) and High Zagros Reverse Fault (HZRF). It also recognizes several new lineaments that have not been previously reported such as (L3, L4, L5, L8, L9, L12 and L15).
- Some proven regional longitudinal and transversal faults are best mapped using magnetic data only (e.g. SF and HZRF) or gravity data (e.g. KF, ZMFF, BBTF and STF), whereas other faults are identified using both gravity and magnetic data (e.g. AQDF).
- Many Zagros folds plunge and terminate at the intersection with some of these derived transversal NE–SW-trending lineaments. However, other folds crossing these lineaments are bent by them.
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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES


**SUPPORTING INFORMATION**

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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