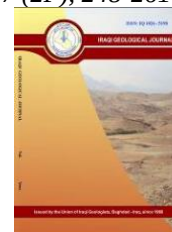




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Deducing the Total Magnetic Intensity Field for Visualizing the Crustal Rocks Setting of Iraq from the World Magnetic Model 2023

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Abstract

This research includes the derivation of an updated total magnetic intensity map of Iraq given from the satellite data. The World Magnetic Model (WMM), 2023 which was obtained from satellite orbitography adopted to determine the total magnetic intensity field (F) values for each grid point that covered the whole study region of Iraq. The WMM software was used to calculate the F value for 272 grid points that covers the whole study region. This region was gridded with suitable interstitial distances of 50 Km to cover such region representatively. The calculations of F were achieved in two steps. The first step represents the F calculation at sea level (altitude=0), whereas the second one calculated the F by considering the elevation meter value of altitude for each grid point. It was proposed to deduce the residual F by subtracting these values at altitude = 0 field from that altitude field. Then, the deduced residual surface was reflected the magnetic intensity variations across the study region for the rocks overlain the reference ellipsoid. Residual F surface was treated mathematically within the 2D domain by using the software. The results were provided a vision of the highest and lowest gradients of F and for interpreting their variations were shown to be coincided with the major tectonic boundaries of Iraq that been detected by previous studies. The given values of F were found to be mostly dependent on the magnetic susceptibility subsurface basement and / or crustal rocks depth. It was concluded that the increase of F values towards the N and NE direction is related to the increasing thickness of crustal rocks or the depth to the Moho discontinuity, and also such thickness or depth is found to be increased towards the E-W direction but with lesser values.

Keywords: Iraq WMM 2023; Magnetic map; Crustal rocks; Iraq; Tectonic Boundaries; Orbitography Magnetic map

1. Introduction

Igneous, metamorphic and sedimentary rocks compose the Earth's crust. Crustal rocks are made of numerous numbers of minerals, but only few ones have relative strong magnetization e.g. Magnetite and Hematite, (Lowrie, 2023). Geologically, some rocks become in contact or around magnetized ore bodies within subsurface structures like faults or igneous intrusions, (Lowrie, 2023). Some parts of continental crust show strong magnetizations which resulted by induced magnetization for some ore bodies by the current magnetic field of Earth, (Lowrie, 2023). Furthermore, oceanic crustal rocks show high magnetic anomalies which represent the permanent magnetization and polarity alteration of lithosphere and reflected at the seafloor rocks during the divergent spreading, (Lowrie, 2023). Rock minerals gain their magnetization when they cool below Curie's temperature which increases with depth (Lowrie, 2023).

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The main magnetic field value varies from about 25 000 nT at the equatorial regions, and reach to the value of about 70 000 nT near poles, (Kearey et al, 2002). Magnetite mineral abundance considered as the most responsible of rock magnetizing when it reaches below its Curie temperature of 578°C, (Kearey et al, 2002). Magnetite grain characteristics like shape, size and abundance which affect its magnetic properties; Magnetization in rocks could be classified according to the magnetic content and behavior in which called the magnetic susceptibility (Kearey et al, 2002).

1.1.Satellite Orbitography of World Magnetic Model 2020- 2025

The World Magnetic Model (WMM) represents mathematically the magnetic potential expansion. Their was represented as a harmonic spherical function to degree of order (12). The wavelength minimum is given by:

$$\frac{360^{\circ}}{\sqrt{12 \times 13}} = 28.8^{\circ} \quad (1)$$

This corresponds the arc length distance at Earth surface of about 3200Km, (Backus et al., 1996; Chulliat et al., 2020). The WMM reflects the Earth's internal magnetic field elements while excluding the disturbing magnetic fields which have a 30⁰ wavelength according to the coverage arc length. The WMM expresses the entire earth's core field in addition to the long wavelengths field which related to the oceanic and continental crust. (Chulliat et al., 2020), mentioned that the expression (main field) is referring to the WMM portion which modeled by taking into consideration the core non linear changes in the magnetic field or what called Secular Variations (SV), therefore, the magnetic elements which belongs to this model is updated each 5 years and the current WMM is valid for the period from 2020 to 2025, (Chulliat et al., 2020).

The WMM is calculated by a list of equations, which are required to obtain the seven elements of the magnetic field. It is also possible to be calculated for the desired time and location for any point at earth's surface, (Chulliat et al., 2020). The information required to be input to the WMM software calculator, in order to calculate the magnetic elements for any point at earth's surface, are: longitude and latitude angles even the elevation above the mean sea level or altitude value in meters. The results of calculation represents F, H, X, Y, Z element values in the units of nT, also the inclination (I) and the declination (D) values. The magnetic elements are calculated by using the following equations:

$$F = \sqrt{H^2 + Z^2} \quad (2)$$

$$H = \sqrt{X^2 + Y^2} \quad (3)$$

$$D = \arctan (X/Y) \quad (4)$$

$$I = \arctan (Z/H) \quad (5)$$

The software which calculates the magnetic elements is available online and supported by the National Oceanic and Atmospheric Administration (NOAA) / National Centers of Environmental Information (NCEI). The World Magnetic Model WMM represents a cooperative continuously developed product of the United States' National Geospatial-Intelligence Agency (NGA) and the United Kingdom's Defense Geographic Centre (DGC) in addition to the (NCEI) and the British Geological Survey (BGS). The currently used WMM online magnetic elements calculator software is available and allows user to compute all the values related to earth's magnetic field for any point within the spatial domain, also at any period of time between the date of model release and the year 2025. Input and output with various formats are available, as well as, the availability of web-based Application Programming

Interfaces (API). The accurate world magnetic model is based on measuring the vector components of the earth's magnetic field with a good global coverage and less levels of noise. Therefore, Swarm mission in November 2013 has launched 3 satellites by the European Space Agency (ESA). This system considered as the most effective one in observing the global magnetic field variations. However, the Swarm system is capable of monitoring the magnetic elements on hourly basis, so it may be considered as important tool for monitoring the geomagnetic field variations with time.

The Swarm is composed of 3 satellites which fly near the polar orbits as A, B and C. According to the late 2019 position, A and C satellites were at the 87.4° in inclination and their altitude was about 450Km. The satellite B is higher in position than satellites A and C and was in the inclination of 88° with altitude of 500Km. Each of the satellites weighs about 468Kg and about 9m in length. (Fig. 1) shows one of the previously mentioned satellites (Chulliat et al., 2020).

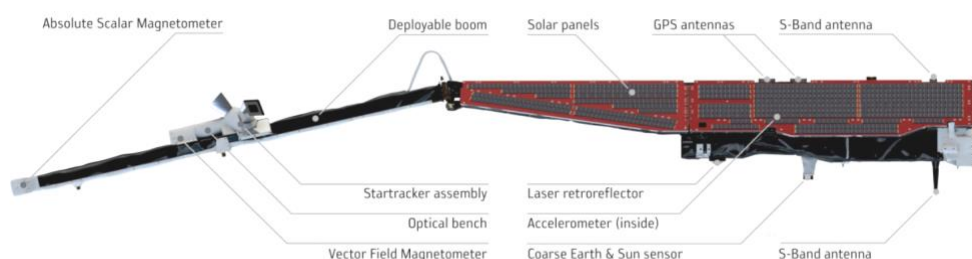


Fig. 1. Swarm satellite showing the Absolute Scalar Magnetometer (ASM) which is mounted at the tip of the satellite arm, while The Vector Fluxgate Magnetometer (VFM) is mounted in the middle of satellite arm. The distance between the scalar and vector magnetometers is about 1.6 m (Chulliat et al., 2020).

Each of the Swarm satellites (Fig. 1), is equipped with a Vector Field Magnetometer (VFM) which manufactured by the Danish Technical University. The VFM is a tri-axial fluxgate magnetometer having a sampling rate of 50Hz, and accuracy of about (1nT) after calibration. It is mounted in the middle of the satellite arm. Furthermore, an Absolute Scalar Magnetometer ASM is mounted on the tip of satellite arm and used to perform the absolute calibration for the vector devices. The (ASM) includes redundant sensor which manufactured by the French Atomic Energy Commission for the benefit of French National Center of Space Studies (CNES). The ASM is an optically pumped meta-stable He-4 magnetometer with sampling rate ranging between 1 and 250 Hz , resolution of about 0.1nT and accuracy of about 0.3nT (Chulliat et al., 2020).

1.2.The Geophysical Properties of Crustal and Basement Rocks in Iraq

The basement rock types composition was studied by Jassim and Goff (2006)(Fig. 2), in which it deduced from the aeromagnetic data processing and interpretation. Basement rock types of Iraq are oriented as stripe shaped areas which are elongated in the NW-SE direction which is affected by the tectonic force action in the general direction from SW towards NE. It was observed as that the post tectonic related rocks Gabbro and Diorite which composes the most NE part of basement rocks and covering the areas of Duhok, Mosul, Erbil and Kirkuk Cities. Such rocks have higher magnetic susceptibility as compared to the other basement rock types presented as purple colour in the map of Fig. 2, which represent the basic igneous rocks, therefore they may have the highest magnetic susceptibility, as shown in the figure above. Towards the SW, lower magnetic susceptibility rock stripes show up consequently the Granite (red colour), metamorphic phyllite-schist and granodiorite (light pink colour), and relatively thin stripe shaped inclusions of Ophiolites and syn-tectonic gabbros small inclusions (violet colour). Towards the west of Iraq, the basement rock stripes became directed towards

N-S direction and described from the east to the west as metamorphic phyllite rocks (Green colour), then a sequence of thinner stripes of granodiorite-granite (orange colour) and Murdama molasse (light blue colour) as well (Fig. 2).

Murdama group represents a sequence of Proterozoic layered rocks; it consists of clastic sedimentary rocks with smaller amount of limestone and volcanic rock fragments. It is usually overlies older plutonic igneous rocks like diorite and granite, (Greene, 1993).

The depth to the top of crystalline basement rocks of Iraq decreases particularly at the mountainous stripe at the most NE part of Iraq. By observing the map of (Fig. 3), most parts of northern Iraq particularly having a depth to the top of basement rocks of about 5Km (orange colour), while the less parts are deeper than this value. This complex picture is the result of the tectonic force action in the region in which the general direction of SW-NE is almost vertical to the basement rock strips elongation at the NW-SE direction.

By observing the map of Fig. 3, one may also detect the middle part of Iraq stripe of shallower basement rocks which detected by analyzing gravity data of previous studies. This stripe extends in the NE-SW direction and particularly in the middle areas of Iraq which separates the stable shelf from the unstable shelf. It represents the depth of about 5Km and appears in the deep orange colour which refers to shallower basement rocks as compared to the other parts of Iraq.

It is worth to mention that the shallower basement rocks did not necessarily produce an increase in the regional magnetic intensity values because the latter was depend on the crustal rock type magnetic susceptibility and its thickness.

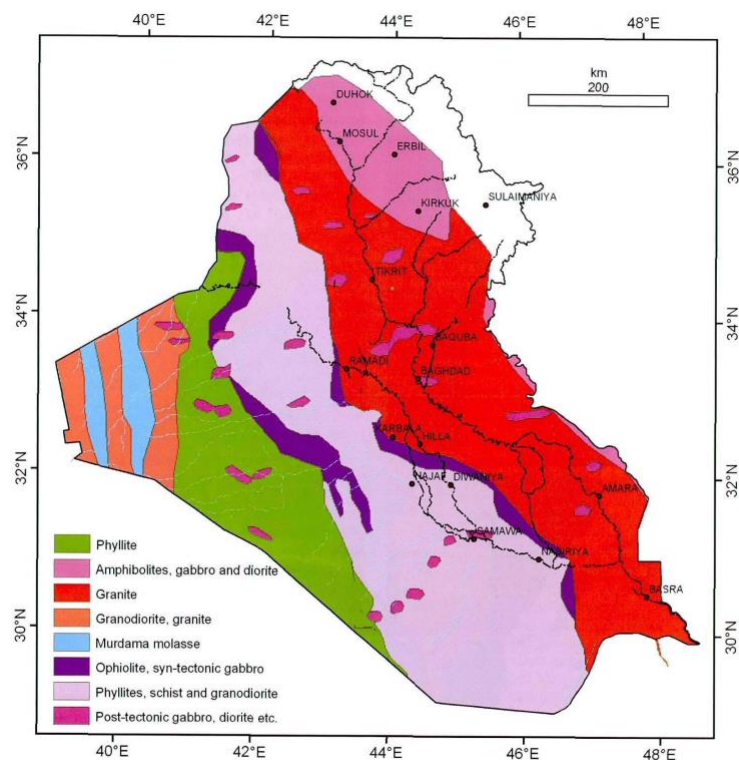


Fig. 2. Basement rocks composition of Iraq deduced from aeromagnetic data processing and interpretation (Jassim and Goff, 2006)

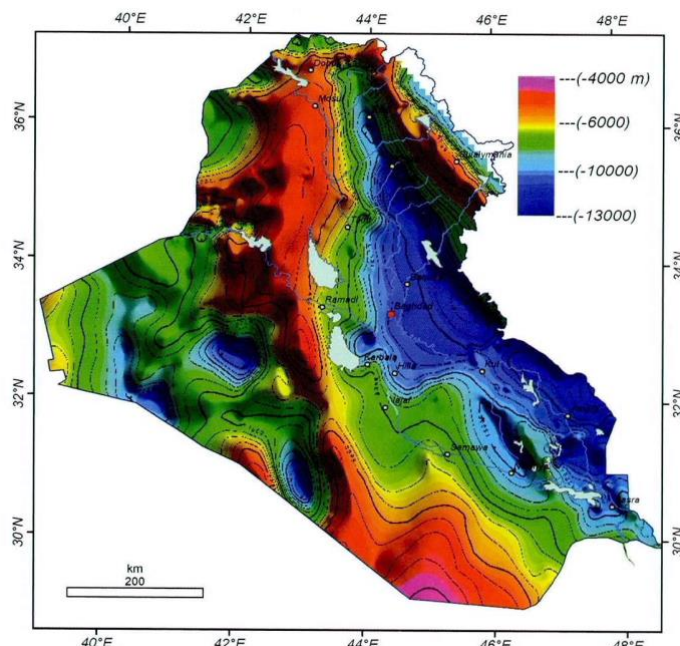


Fig. 3. Depth to crystalline basement rocks which belongs to Precambrian relatively to sea level in meters deduced from analyzing gravity data (Jassim and Goff, 2006)

The shallower basement rocks may increase the magnitude of local anomalies detected by aeromagnetic surveying rather than regional ones which visualized by the upward 500Km altitude (F) using satellite orbitography.

The depth to the Moho discontinuity in Iraq was also studied. (Abdulnaby et al. 2020) have studied the crustal structure of the Mesopotamian plane by analyzing teleseismic data of 33 seismic stations located inside and around Iraq, (Fig. 4). By observing this figure one can conclude that the highest depth of Moho discontinuity shows up at the northern and northeastern part of Iraq particularly on the Zagros belt portion which represents the zone of collision between the Arabian and the Eurasian plates. The depth to Moho discontinuity found to reach about 55 Km.

Another study was achieved to detect the crustal rocks thickness of Iraq given by (AL-Banna and AL-Heety, 1994) from analyzing gravity data. The results were presented as a contour map referring to the crustal thickness variation in Iraq, (Fig. 5). By observing this figure one can detect that the thickest crustal basement rocks shows up at the most northeastern part of Iraq. At the same time it is noticed that the crustal rocks thickness decreases towards the south and southwestern parts, meanwhile the thickness increases towards the western part.

(Al-Banna and Ali, 2018), in another study according to the gravity data interpretations, displayed the locations of the tectonic boundaries that separated the stable zone from the unstable zone. The separating boundary is located at the western side of Iraq and this boundary extends towards the southwest direction of the Euphrates River as well, (Fig. 6).

The major aim of this study is to interpret the Total Magnetic data in order to generate a vision about the crustal rocks and connecting the current regional magnetic intensity results with the geophysical properties of crustal rocks that obtained from the previous geophysical studies in Iraq, as well, to detect the degree of compatibility between the current results of the Total Magnetic Intensity variations with the previous geophysical local magnetic, gravity and teleseismic studies concerning the status of crustal basement rocks in Iraq.

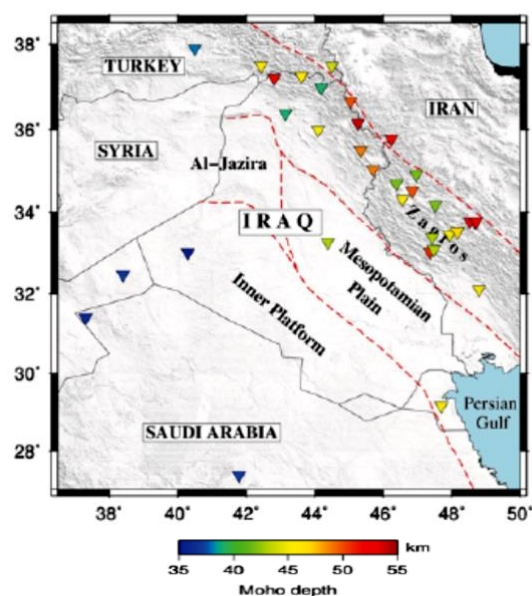


Fig. 4. The depth to Moho Discontinuity map derived by analyzing teleseismic data of 33 seismic stations, the triangles refers to seismic station locations while the color of triangle refers to Moho depth at the station (Abdulnaby et al. 2020)

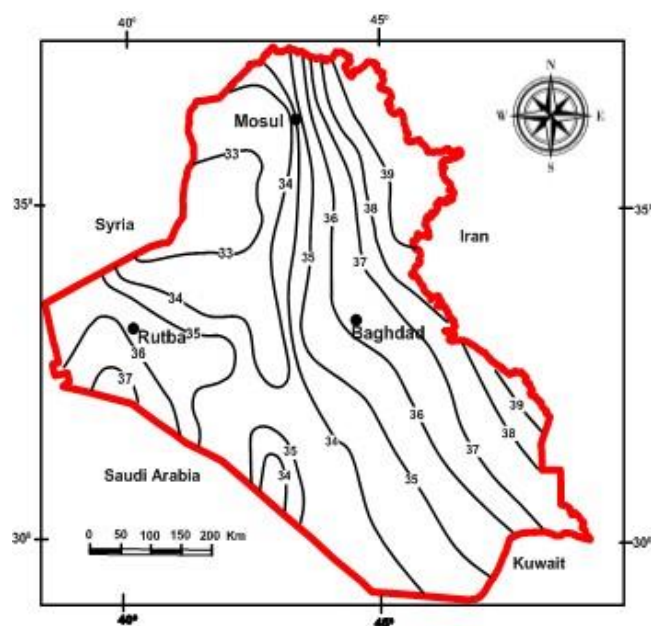


Fig. 5. Crustal thickness of Iraq basement rocks derived from gravity data (AL-Banna & AL-Heety ,1994)

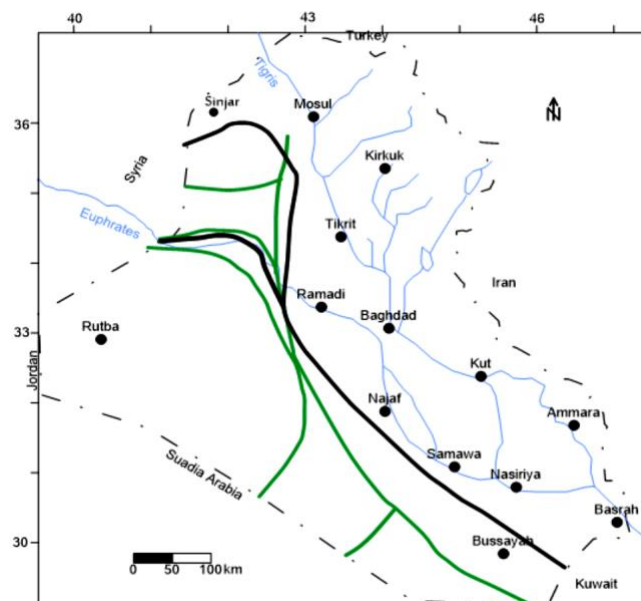


Fig. 6. The tectonic boundaries published by (AL-Banna and Ali, 2018), black line represents the boundary line assigned by several previous tectonic maps. Green line assigned from gravity data interpretation.

2. Materials and Methods

The Earth's main magnetic field could be expressed as (B_m) vector force for a certain point within the space. B_m could be described by seven magnetic components as shown in the (Fig. 7). These elements are: the horizontal intensity (H), total intensity (F), northern intensity (X), vertical intensity (Z), eastern intensity (Y), inclination angle (I) and the declination angle (D), (Chulliat et al., 2020).

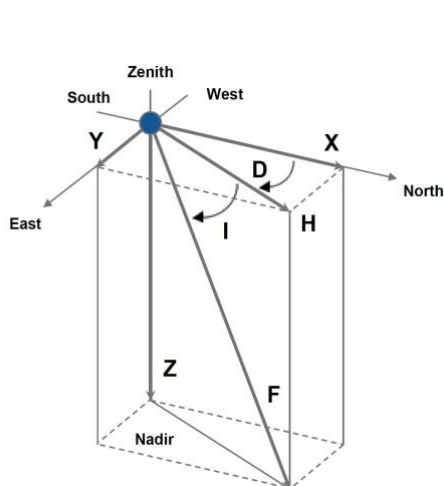


Fig.7. Elements of the geomagnetic field. The B_m vector is associated with an arbitrary point within the space (Chulliat et al., 2020)

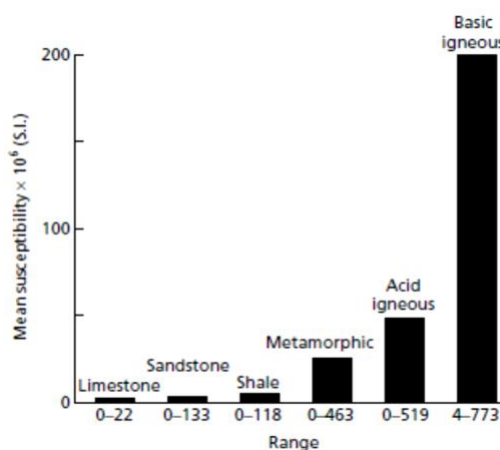


Fig.8. The mean values and ranges of common rocks magnetic susceptibility (Dobrin and Savit, 1988).

Magnetized rocks which contains magnetic minerals have both induced and remnant magnetism. The mean value ranges of magnetic susceptibility for most common rocks in nature are presented in the histogram as shown in (Fig. 8). Relative magnetic intensity for both induced and remnant components are commonly expressed in the terms of the Königsberger ratio: ($J_r : J_i$). These magnetic intensities are different in direction and magnitude. The total magnetic intensity field of the rocks represents the resultant (J) for the two vectors, (Fig. 9). The resultant force of J produces magnetic anomaly amplitude, while (J) direction effects the anomaly shape, (Kearey et al. , 2002).

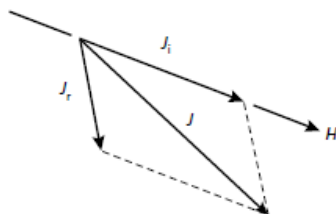


Fig. 9. a diagram of vector relationship between induced magnetization (J_i) and remnant magnetization (J_r) and the resulted total magnetization (J), (Kearey et al , 2002).

In the current research, a grid pattern composed of 272 stations with interstitial distance of 50Km was prepared to cover the whole region of Iraq. The data was tabled in order to be prepared for using in the (NOAA) magnetic elements calculations. It was required to provide the coordinates and altitude values for every station within the grid pattern to input into software calculator. The online software calculator was provided by the (NOAA, 2023). The magnetic field calculators facility offers the calculation of magnetic elements that were related to the International Geomagnetic Reference Field (IGRF) for the period (1590-2024), the Enhanced Magnetic Model EMM for the period (2000-2019) and the World Magnetic Model WMM (2019-2024) which then used in calculating the total intensity element (F) for each grid station separately in the current research. (Fig. 10) shows the window of the magnetic calculator which was used to calculate the total magnetic intensity and the other elements of the geomagnetic model. The data were set to be calculated on the date of 26/September/2023 when calculating the F values. The calculator was used in two options that concerning the choos of the elevation above sea level. Once the whole data set were calculated at the mean sea level, and the second is by inputting the altitude value for every grid station. When the altitude was set to be at the mean sea level, this will calculate the regional (F) variation at the reference level or the mean sea level, then a regional F map at the reference level was conducted, as shown in (Fig. 11).

Fig.10. The Magnetic field calculator online window, (NOAA, 2023).

The GPS option which related to the altitude requires the availability of elevation above sea level in meters for each station within the grid. This option is used to deduce the total intensity (F) map within the altitude level.

3. Results and Discussion

The deduced total intensity map of Iraq gives a general vision about the magnetic susceptibility variation for the crustal rocks. It was important to deduce the map, (at reference level F), at first by considering altitude = 0 m, this represents the total magnetic intensity variations at the reference ellipsoid level. However, the generated regional (F) map is shown in (Fig. 11).

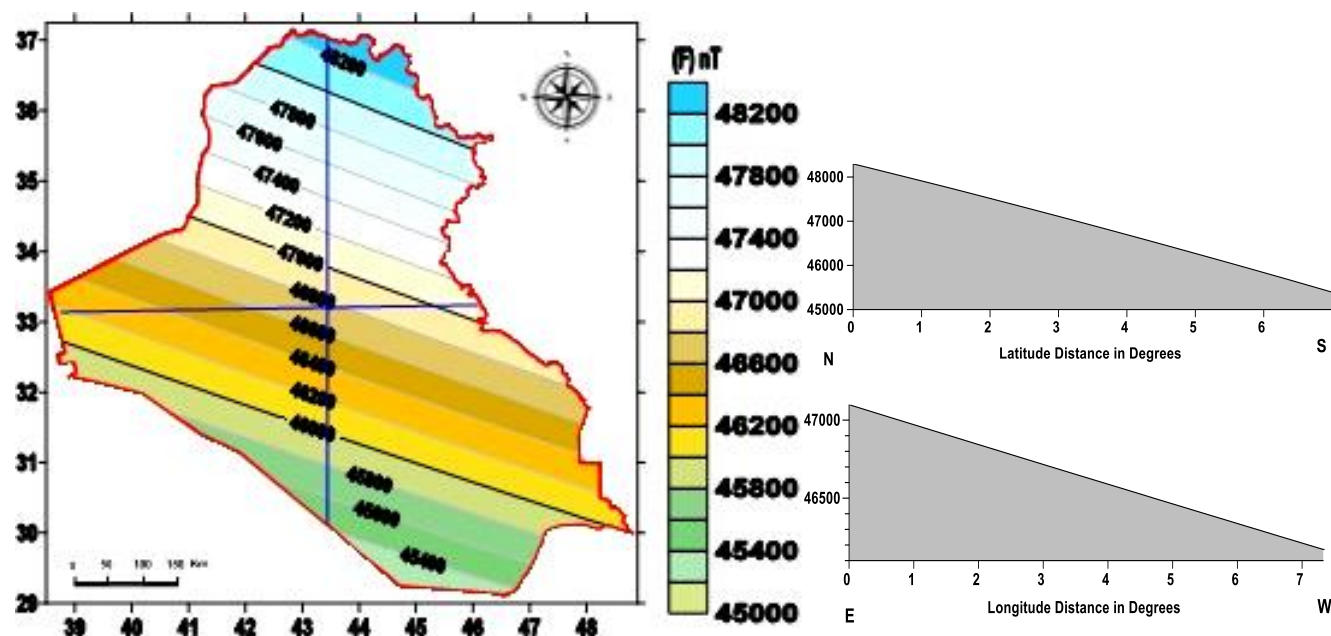


Fig.11.The calculated Regional (F) map at reference level at (Altitude = 0m).

By input the altitude values to the F calculator for the same previous grid nodes, another map of total intensity is produced, which represents the F at the altitude field, (Fig.12).

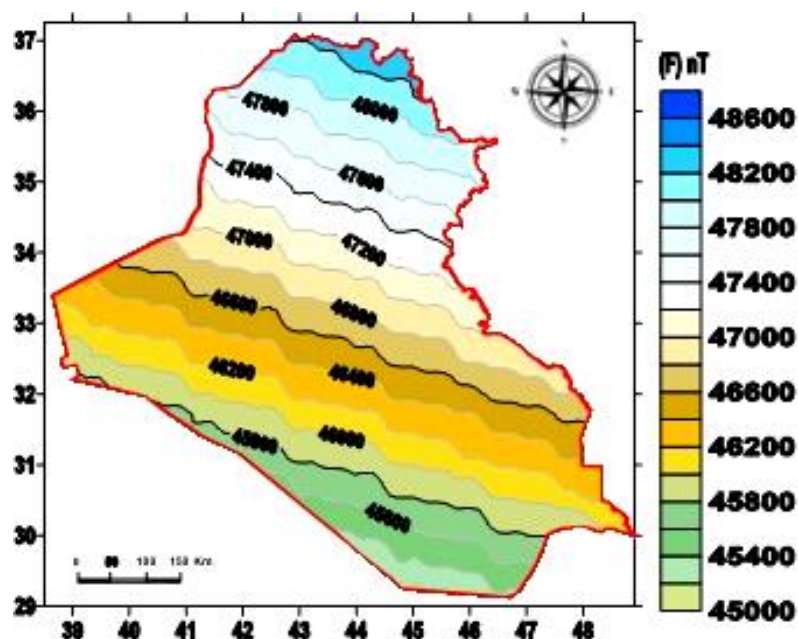


Fig.12. The Total magnetic intensity (F) map at altitude of the current study.

By subtracting the F field of Fig. 11 from the F at altitude of Fig. 12, a residual F field was produced, as shown in Fig. 13 below.

The residual magnetic intensity map expressing the F values variation for the crustal rocks thickness is found to be bounded between the reference ellipsoid level and the ground level which is measured in meters above sea level or reference level. This map shows some major anomalies which were related to the variations of the magnetic susceptibility of the crustal rocks. Such variations are caused by some reasons like: basement rocks type and depth, thickness of the crustal rocks above the reference level, and thickness variations affected by the tectonic force action which mainly producing folding and faulting within the crustal rocks of Iraq as well.

Residual intensity map provides a magnetic susceptibility image about the sedimentary cover rocks according to the upper part of crust rocks and sediments. By observing (Fig. 13), the magnetic intensity of the crustal rocks which bounded between the reference level and the altitude could be classified into three main zones, which are:

- Low magnetic susceptibility zone in which magnetic intensity values ranging between 1 and 7 nT. This zone represents the Mesopotamian plane region which is mainly composed of sediments characterized by high thickness of sedimentary cover. Its residual magnetic zone appears in the grey and yellow colors in the map. of Fig. 13.
- Moderate magnetic susceptibility zone in which its residual intensity values ranging between 7 and 22 nT, it appears in green color in the map of (Fig. 13), it refers to a thinner sedimentary cover and relatively shallower basement rocks.
- The highest magnetic susceptibility zone of the residual intensity values were ranged between 22 and 49 nT or more. It is the closer to surface basement rocks zone and the thinnest sedimentary cover zone.

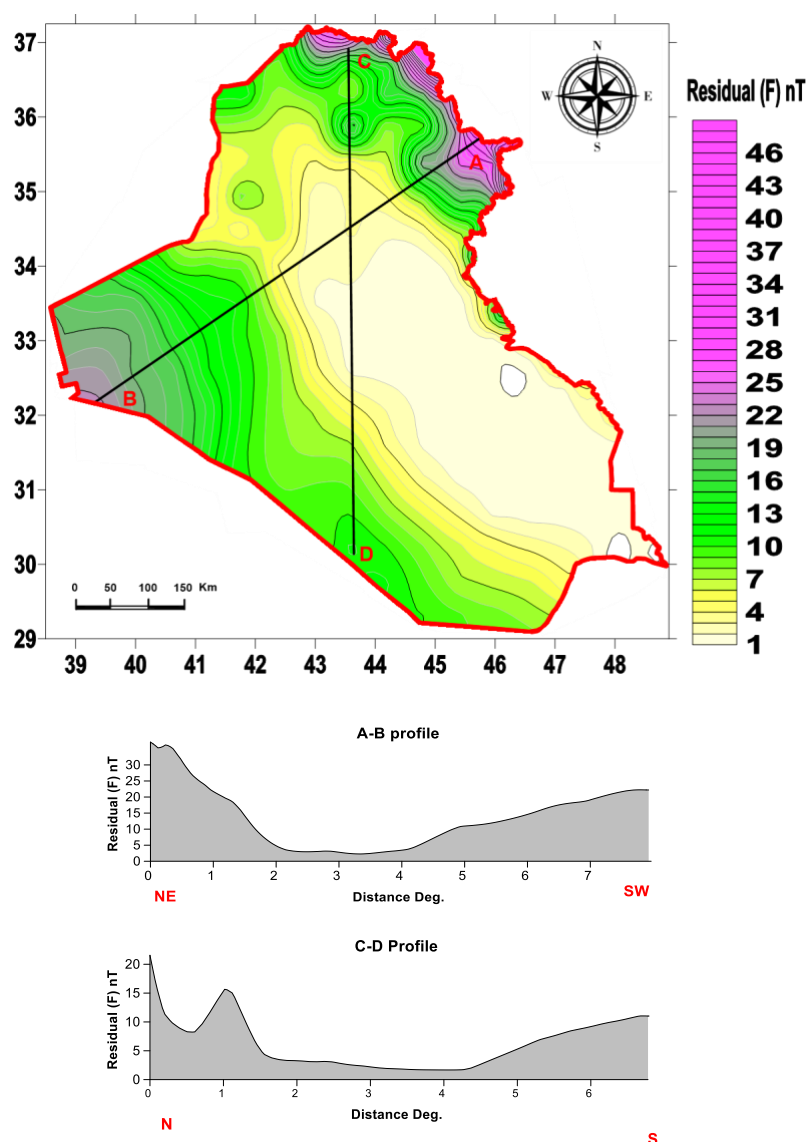


Fig. 13. The deduces residual magnetic intensity (F) map of the current study , (A-B) and (C-D) profiles showing the residual magnetic variations across the distance.

- The highest magnetic intensity appears at the NE and N parts of Iraq and are slightly high values at the most western part.
- The 1st directional derivative 2D filtering was applied in the direction E45°N or S45°W. The NE-SW direction was chosen in order to visualize the best variations in the residual magnetic intensity across the region. The aim for applying such filter is to detect the locations of high and low gradient zones (Fig. 14).

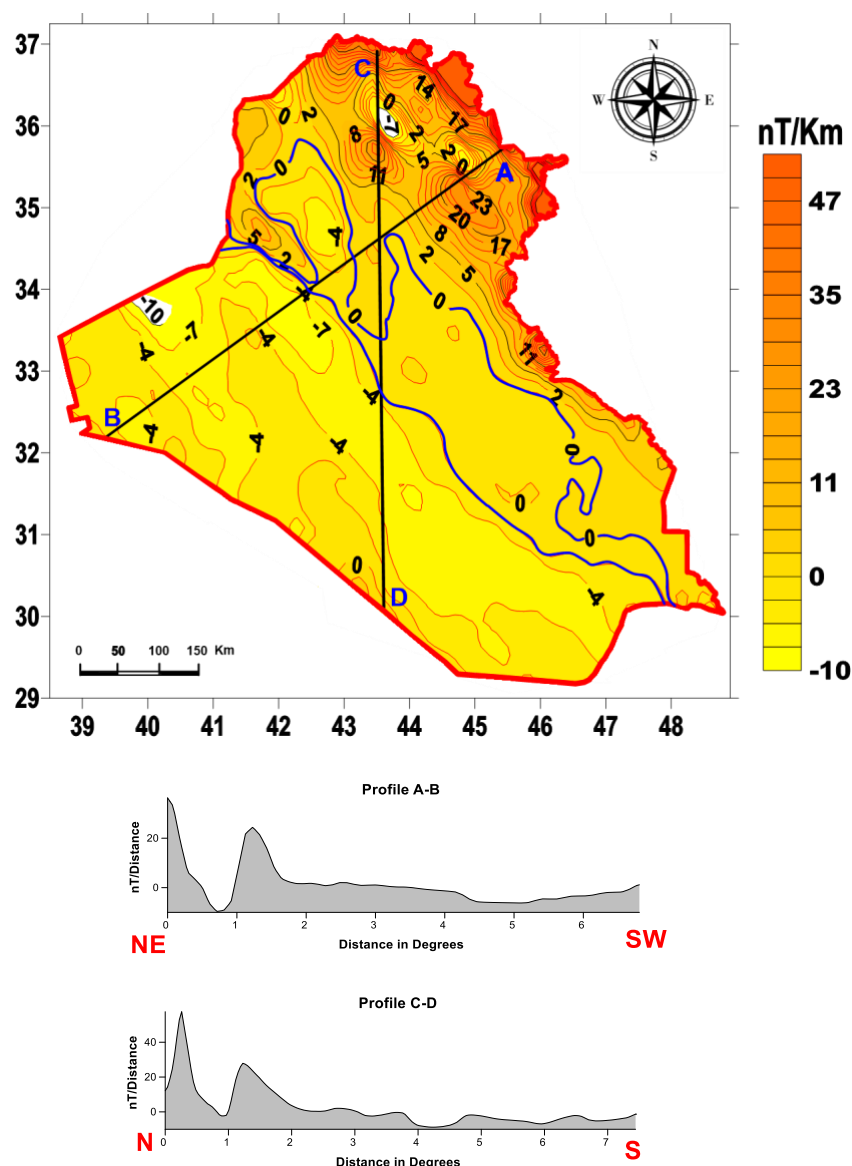


Fig. 14. The 1st directional derivative applied to residual (F) map, showing the high and low gradient locations. Directional derivative direction was NE-SW in order to show the best variation results, (A-B) and (C-D) profiles showing the magnetic gradient across the distance..

Potential fields gradient or directional derivative maps represent an effective tool in detecting high and low gradient anomalies as given by (Al-Khafaji and Al-Yasi, 2021; Al-Khafaji, 2017). Well, by observing the map of Fig. 14, a zero contour line value (blue color line) was surrounded a region with no gradient in magnetic susceptibility. The region surrounded by this contour line represents a large part of the Mesopotamian plane which also shows a low range of residual magnetic intensity values (Grey color zone) in the Fig. 13. The SW part of the zero gradient contour line is almost coinciding with the tectonic boundaries that published by Al-Banna and Ali (2018) and previously shown in Fig. 9. Therefore, this boundary is considered an important indication as it separates between the stable and unstable shelves according to the tectonic setting of the region.

High gradients impact were clearly appeared towards the most NE and N parts of Iraq which shows positive values in the terms of (nT) per distance as reach to about 50 nT/Km. Negative gradient

values, on the other hand, were found towards the W and SW parts of Iraq, this is mainly caused by the tectonic force action which affects to make variable depth for the basement rocks.

4. Conclusions

The deduced intensity map at reference level from the 2023 WMM model represents a regional variation map of magnetic intensity and visualizes its very large scale variations which related to the crustal rocks of Iraq. It provided a vision about F variations were taken from the elevation of satellite mounted magnetometers in the elevation of 450-500km above the sea level. Therefore, such map doesn't show any local anomalies, but only the regional variations in the magnetic susceptibility. Regional F values were generally increased to reach about 48600 nT at the most NE part of Iraq, whereas F values were decreased towards SW and S directions to reach about 45000 nT.

The increase of (F) values towards the NE direction may be related to the NE part of Iraq that is composed of basic igneous rocks which have higher magnetic susceptibility as compared to the other parts, constituents of basement rock types within the crustal rocks of Iraq. This may be related to the higher tectonic impact at the NE part of Iraq, also, this has been approved when deducing the magnetic intensity maps at the reference level and these at altitude magnetic intensity maps. The altitude magnetic intensity values were increased as the crustal rocks and increased in thickness towards the NE direction due to the effect of tectonic action, which mainly produced by the collision between the Arabian and Eurasian plates at the Zagros belt or the high folded zone regions. This has been approved by the previous gravity studies in Iraq. Thicker crustal rocks in turn may have higher amount of magnetite or ferromagnetic minerals, therefore, it has higher magnetic susceptibilities and higher F values as well.

The deepest Moho discontinuity is found at the NE part of Iraq. This was approved by previous teleseismic-tectonic studies in Iraq. Also, the general shallower depth to the top of basement rocks at the mountainous NE and N parts of Iraq was approved by the previous local magnetic studies. Deeper Moho discontinuity and shallower depth to the top of the basement rocks means thicker crustal rocks towards the NE direction and larger amount of basic crustal rocks at this part, which produces higher magnetic susceptibility and higher F values.

The deduced residual field (F) also visualized the magnetic variations which confined between the reference level and the altitude level, this was helpful in the zoning of the highest, moderate and low residual magnetic intensity across the region.

By applying the 1st directional derivative filtering on the residual field (F), it was possible to detect the zero gradient boundaries which almost coincides with the tectonic boundaries and it was compatible with the previous tectonic setting, gravity interpretations and geo-tectonic studies. The NE part of the Mesopotamian plain appeared to be surrounded by the zero gradient value boundaries as shown by Fig.14. The low magnetic gradient over the Mesopotamian plain refers to a thicker sedimentary cover and deeper basement rocks, therefore, it has lower magnetic intensity. This also clearly appears in the residual F map (Fig. 13), where magnetic intensity values were ranged between 1 to 2 nT or lower values over the Mesopotamian plain.

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