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Using of Gradient Techniques for Depth Estimation of Gravity Source

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Abstract:

A new method, depends on the determination of the horizontal and vertical gradients of gravity data, is introduced for estimating the depth of gravity source. The distance of the nearest intersection point, of horizontal and vertical gradient, to the central axis of the gravity anomaly (x) is found to be related directly to depth of gravity source. Two relations were obtained to estimate the depth of the source that is approximated to spherical or horizontal cylinder bodies. The suggested method is applied on four groups of gravity data, where the depths to the sources are well known, and the results are generally confirming the actual depth.

The introduced method is applied for two gravity anomalies in Iraq of which the depth is unknown and acceptable results are obtained.

Introduction:

The role of gravity gradient in structural interpretation of gravity has been started since the papers of Evjen(1936). Many publications described procedures for calculating gravity gradients from measured gravity data using numerical filtering method such as Agarwal and Lal (1972a). Green (1976) and Klingele et al (1991) has been used the gradient techniques for two dimension(2-D) structural interpretation of truncated plate model. Fajklewicz (1976) and Butler (1984b) have been used the gradient technique for the detectability, resolution and mapping of shallow geologic features.

Gravity gradient can be measured in the field using gravimeter and special tower for detecting features at depth less than 15 meters, (Butler,1983 and Al-Banna,1996). The gravity gradient also can be determined from the existing gravity data. The horizontal gradient can be determined using suitable horizontal interval from gravity profile. The vertical gradient then can be determined using Hilbert transform of horizontal gradients.

Butler (1995) presented a general procedure for analyzing gravity gradient profile over 2-D structures. This method consists of identifying corners in the structural model from the vertical gradient profile and then using the gradient space plot to determine the structural dips and other key points defining the model. This procedure completely defines the geometry of subsurface structure without any assumptions regarding densities. The gradient analysis procedure suggested by Butler is applied to a gravity data over a sedimentary basin. The results of the gradient analysis procedure is a structural model that is qualitatively consistent with the result of an independent three dimension(3-D) interpretation of the gravity anomaly, however, depths to the graben bottom are larger by a factor of two in the gradient model, (Butler ,1995).

The present study introduces a new method to depth estimation of gravity source using the gradient technique data.

Bases of the method

Hammer and Anzoleaga (1975)discussed the application of gravity gradient for determinated both position and depth pinchout stratigraphic traps.The horizontal and vertical gradients of every gravity anomaly profile are intersecting in three points. The nearest intersection point to the center of the gravity anomaly is the only one that has a constant distance from the center, in spite of, using various interval of determination of horizontal gradient,(Al-Banna,1996). In order to clear up the above mentioned fact the gravity profile of northern Hamrin anticline, in northern part of Iraq, is considered for horizontal gradient determination with various interval distance 1,2 and 3 Kilometers. Then, the vertical gradient is determined using Hilbert transform for the horizontal gradient of the three intervals,(Fig.1). This figure shows the distance (x) between the nearest intersection point and the center of the anomaly is constant irrespective of the spacing used. As the distance of the nearest intersection point of the gradient profiles of the gravity anomaly is constant we suppose that it may be related to the depth of the source, which is constant for certain mass in the nature.

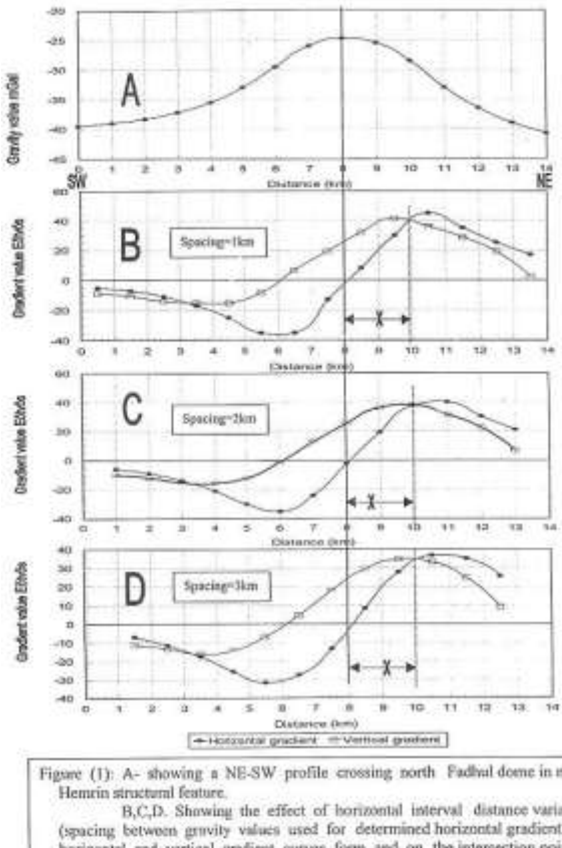


Figure (1): A- showing a NE-SW profile crossing north Fadhal dome in north Hemrin structural feature.
B,C,D. Showing the effect of horizontal interval distance variation (spacing between gravity values used for determined horizontal gradient), on horizontal and vertical gradient curves form and on the intersection point of them relative to the central anomaly axis. This profile is trending northeast Southwest. A crossing the southeastern part of Fadhal elongated dome in north Hemrin structural feature. These profiles show that the distance (x) of the nearest intersection point of gradient profiles is still constant with the variation of spacing used for horizontal gradient determination. which is equal for the considered example about 2.0 km.

In the present study we plan to find the relation between the depth of the source and the distance of the nearest intersection point of the gradient profiles. Therefore, two geometrical bodies are considered to obtain the desired relations, these are:

A. The sphere.

Many geological structures are approximated to spherical body, these are Salt dome, limited sedimentary basin and cavities. The horizontal and vertical gradients of spherical body can be derived from the basic equation of sphere as following:

$$g_z = \frac{4}{3}\pi R^3 \Delta\rho G \frac{Z}{(X^2+Z^2)^{3/2}} \quad \ldots (1) \quad \text{(Nettleton 1940)}$$

$$\text{Let } C = \frac{4}{3}\pi R^3 \Delta\rho G \quad \ldots\ldots\ldots (2)$$

So

$$g_z = C \frac{Z}{(X^2+Z^2)^{3/2}} \quad \ldots\ldots\ldots\ldots (3)$$

Differentiating equation 3 with respect to x and z respectively, give:

$$g_{z,x} = C \frac{-3xZ}{(X^2+Z^2)^{5/2}} \quad \ldots\ldots\ldots (4)$$

(Modified after Butler 1983)

$$g_{z,z} = C \frac{2Z^2-X^2}{(X^2+Z^2)^{5/2}} \quad \ldots\ldots\ldots (5)$$

where g_z= gravity value
$g_{z,x}$= horizontal gradient
$g_{z,z}$= vertical gradient
$\Delta\rho$= density contrast
G= universal gravitational constant
X= the horizontal distance from the center of sphere

Figures 2,3,4,5 and 6 represent the gravity anomalies and horizontal and vertical gradients of sphere of radius 1 meter and density contrast -2.0 g/cm^3, with depths of 1,2,3,4,5 meters respectively.

The distance (x) of the nearest intersection point to the center of anomaly is plotted against the depth, (Fig.7). The following relation was obtained for gravity anomaly source approximated to spherical bodies.

Depth = 1.763 Distance (x)+ 0.026

This relation is applied for all gavity anomalies approximated to sphere geometrical body.

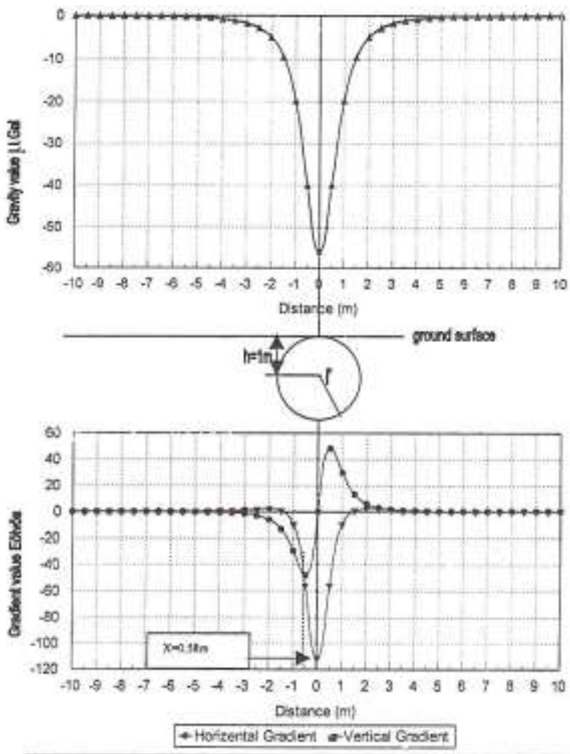


Figure (2) : The gravity effect, Horizontal and Vertical gradient values with the distance for spherical body of Radius (r)=1m, $\Delta\rho$=-2.0 gm/cm^3, and depth (h)= 1 meter, X= distance of intersect point between horizontal and vertical gradient that is close to the gravity anomaly center = 0.58m .

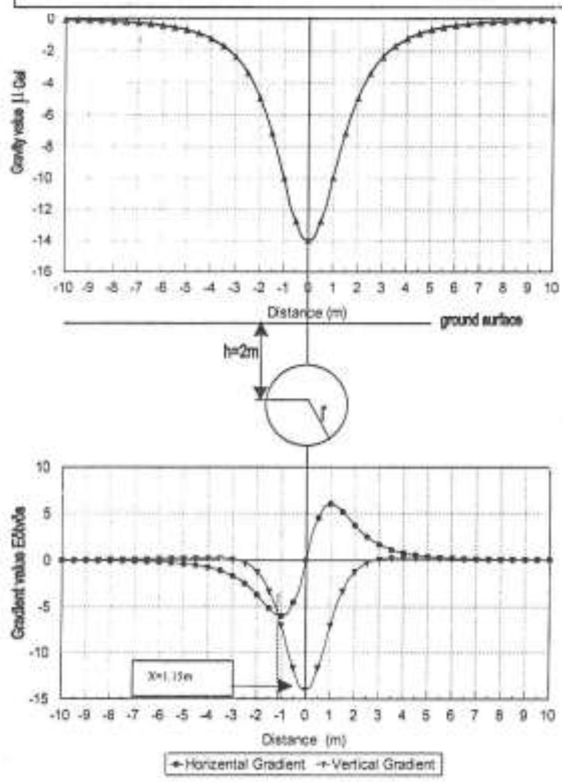


Figure (3) : The gravity effect, Horizontal and Vertical gradient values with the distance for spherical body of Radius (r)=1m, $\Delta\rho$=-2.0gm/cm^3, and depth (h)= 2 meter , X= distance of intersect point between horizontal and vertical gradient that is close to the gravity anomaly center = 1.15m .

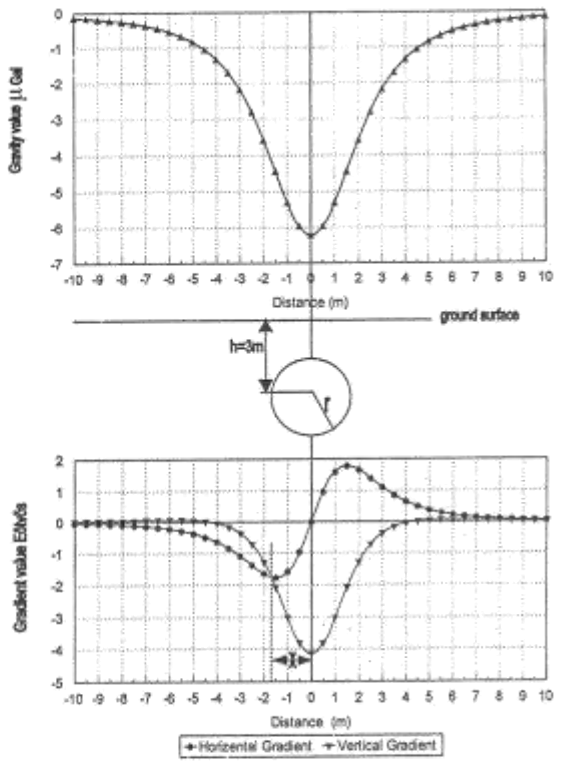


Figure (4) : The gravity effect, Horizontal and Vertical gradient values with the distance for spherical body of Radius (r)=1m, $\triangle\rho$=-2.0gm/cm^3, and depth (h)= 3 meter , X= distance of intersect point between horizontal and vertical gradient that is close to the gravity anomaly center = 1.71m .

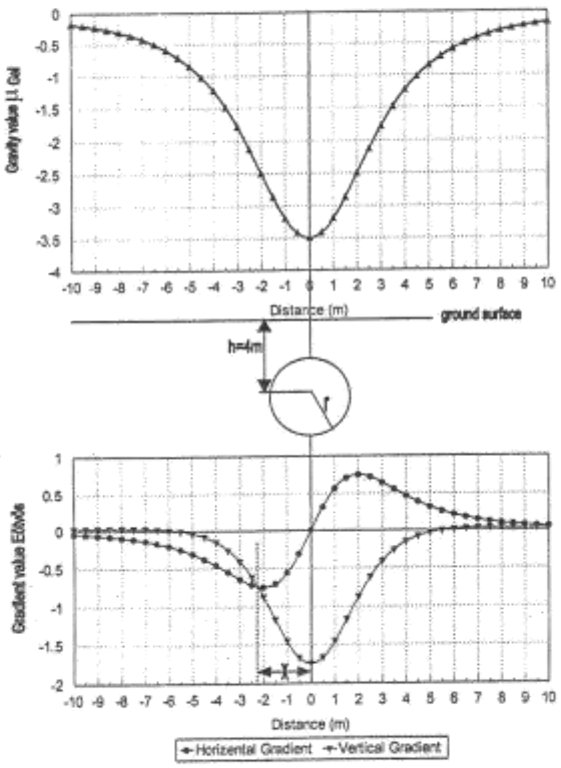


Figure (5) : The gravity effect, Horizontal and Vertical gradient values with the distance for spherical body of Radius (r)=1m, $\triangle\rho$=-2.0gm/cm^3, and depth (h)= 4 meter , X= distance of intersect point between horizontal and vertical gradient that is close to the gravity anomaly center = 2.3 m .

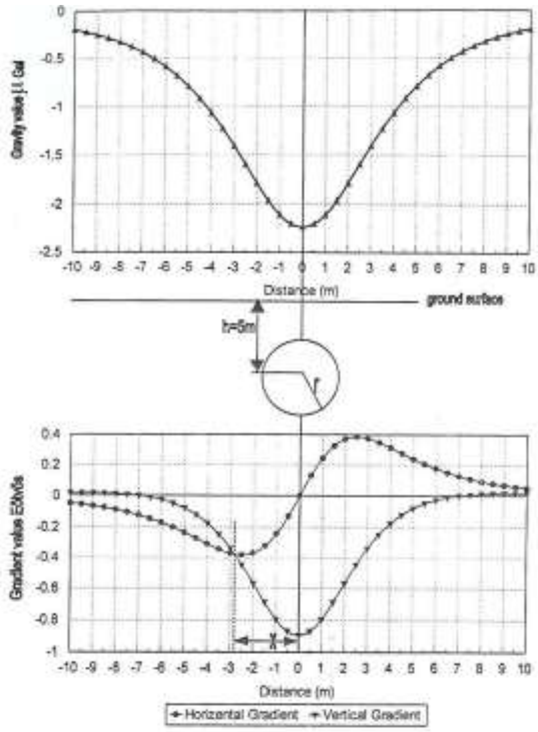


Figure (6) : The gravity effect, Horizontal and Vertical gradient values with the distance for spherical body of Radius (r)=1m, $\triangle\rho$=-2.0gm/cm^3, and depth (h)= 5 meter , X= distance of intersect point between horizontal and vertical gradient that is close to the gravity anomaly center = 2.84 m .

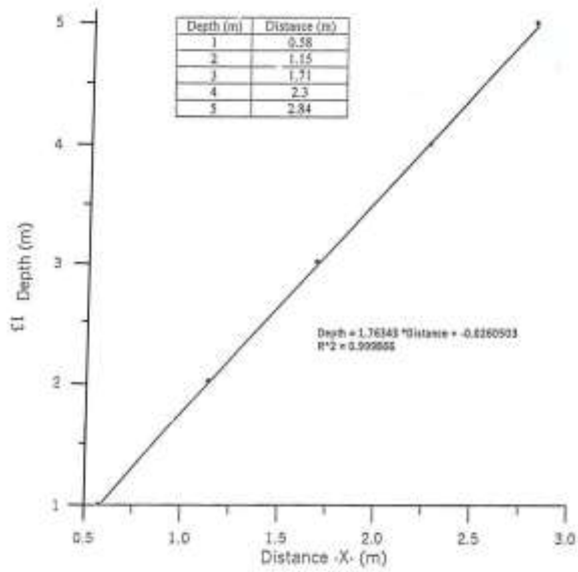


Figure (7): Relation of the nearest intersection of horizontal and vertical gradient to the center of the anomaly (X) with the depth of the center of mass of sphere, radius = 1 meter, density = -2 gm/cm^3

B. Horizontal Cylinder

Many elongated geological structures such as anticline, syncline, elongated basins, graben, horst and buried channel can be approximated to two-dimensional models as a horizontal cylinder. The horizontal and vertical gradient of the horizontal cylinder body can be derived from the equation that is given for gravity effect determination of horizontal cylinder as following:

$$g_z = 2\pi G\Delta\rho R^2 \frac{Z}{X^2+Z^2} \quad \ldots\ldots (6) \quad \text{(Nettleton 1940)}$$

Suppose

$$C_1 = 2\pi G\Delta\rho R^2 \quad \ldots\ldots\ldots(7)$$

So

$$g_z = C_1 \frac{Z}{X^2+Z^2} \quad \ldots\ldots\ldots (8)$$

And (Modified after Butler,1983)

$$g_{z,x} = C_1 \frac{-2XZ}{(X^2+Z^2)^2} \quad \ldots\ldots\ldots (9)$$

$$g_{z,z} = C_1 \frac{Z^2-X^2}{(X^2+Z^2)^2} \quad \ldots\ldots\ldots (9)$$

The variables are as those used for spherical body. Figures 8,9,10,11 and 12 represent the gravity anomaly, horizontal and vertical gradients due to horizontal cylinder of 1-meter radius, -2.0 g/cm^3 density contrast, with depths of 1,2,3,4 and 5 meters respectively. As for spherical body the distance (x) of the nearest intersection point to the center of the anomaly is plotted against the depth, (Fig.13). The following relation was obtained for the gravity anomaly source that approximated to horizontal cylindrical body.

Depth = 2.37 Distance (x)+ 0.029

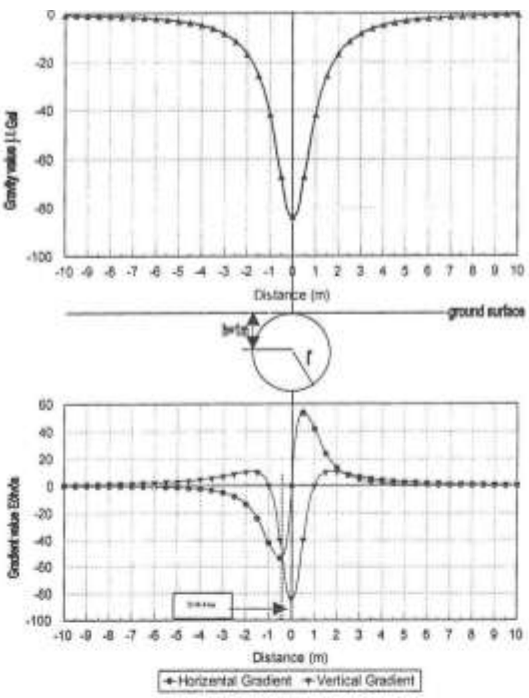


Figure (8): The gravity effect , Horizontal and Vertical gradient values with the distance for horizontal cylindrical body of Radius (r)=1 m, $\Delta\rho$=-2.0 gm/cm^3, and depth (h)= 1 meter, X= distance of nearest intersect point between horizontal and vertical gradient that is close to the gravity anomaly center =0.41m .

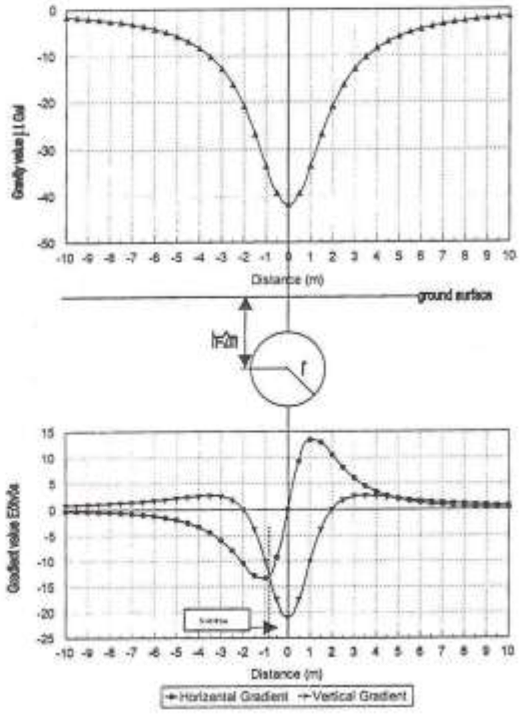


Figure (9) : The gravity effect, Horizontal and Vertical gradient values with the distance for horizontal cylindrical body of Radius (r)=1m, $\Delta\rho$=-2.0 gm/cm^3, and depth (h)= 2 meter, X= distance of nearest intersect point between horizontal and vertical gradient that is close to the gravity anomaly center =0.81 m

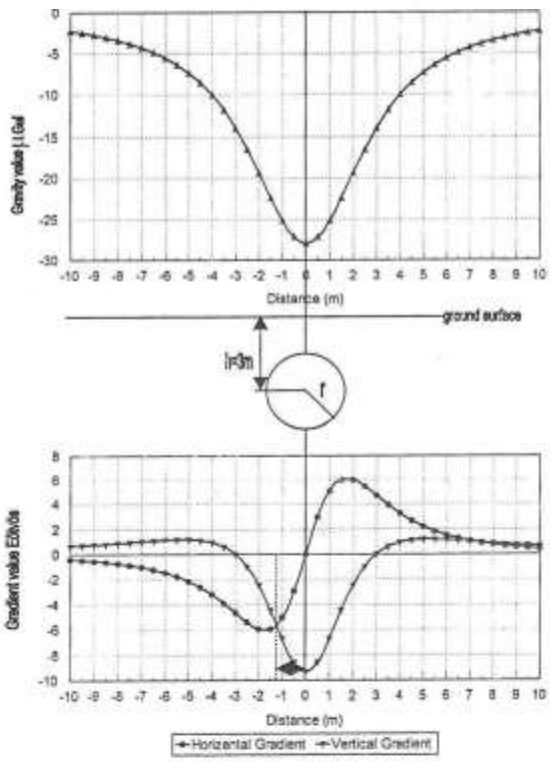


Figure (10) : The gravity effect, Horizontal and Vertical gradient values with the distance for horizontal cylindrical body of Radius (r)=1m, $\Delta\rho$=-2.0 gm/cm^3, and depth (h)= 3 meter, X= distance of nearest intersect point between horizontal and vertical gradient that is close to the gravity anomaly center =1.27m .

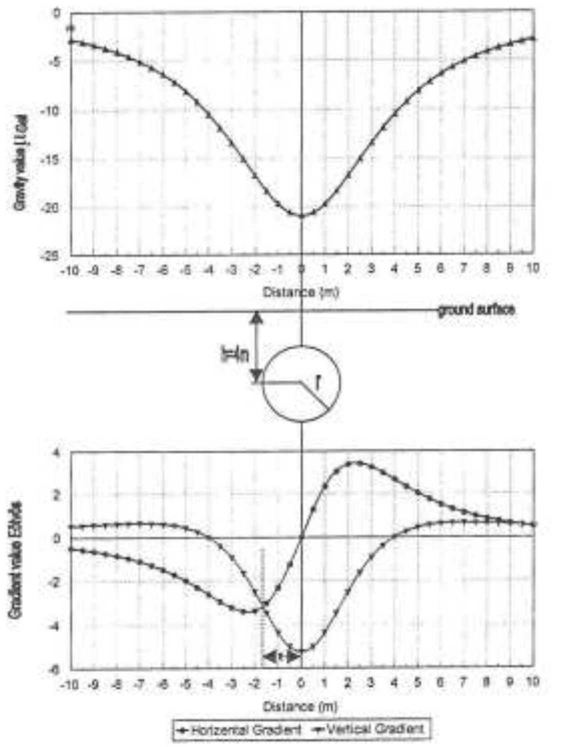


Figure (11): The gravity effect, Horizontal and Vertical gradient values with the distance for horizontal cylindrical body of Radius (r)=1m, $\triangle\rho$=-2.0 gm/cm^3, and depth (h)= 4 meter, X= distance of nearest intersect point between horizontal and vertical gradient that is close to the gravity anomaly center =1.7m .

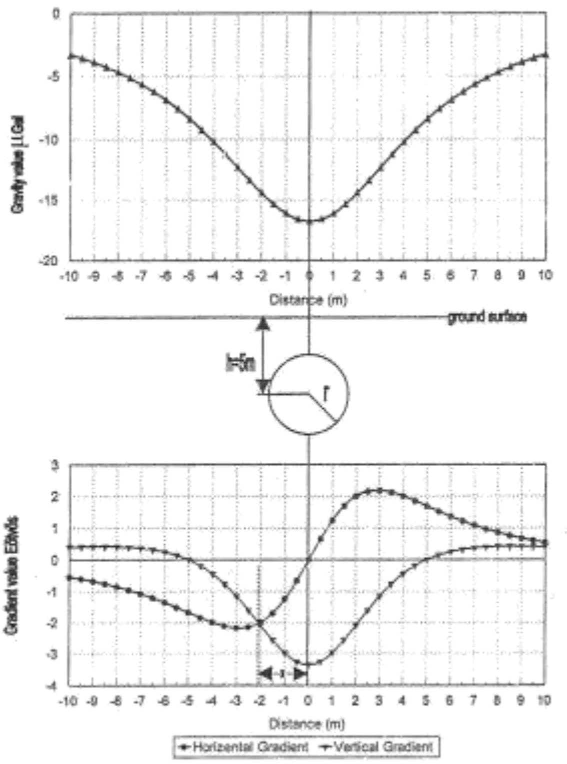


Figure (12) : The gravity effect, Horizontal and Vertical gradient values with the distance for horizontal cylindrical body of Radius (r)=1m, $\triangle\rho$=-2.0 gm/cm^3, and depth (h)= 5 meter, X= distance of nearest intersect point between horizontal and vertical gradient that is close to the gravity anomaly center =2.07m .

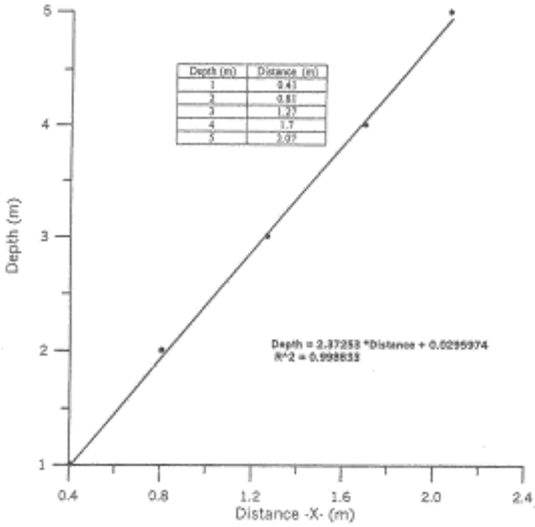


Figure (13): Relation of the nearest intersection of horizontal and vertical gradient to the center of the anomaly (X) with the depth of the center of mass of horizontal cylinder, radius = 1 meter, density = -2 gm/cm^3

Case studies and discusion

To examine the applicability of the suggested procedures, the following four field cases are presented.

1.Rawa cave anomaly:

Rawa cave is subsurface cave in gypsum rock of Al-Fatha formation (Middle Eocene). This cave which is located near Rawa city in the west of Iraq,was studied from Al-Banna(1996). The dimensions of the cave are well known and the depth to the center is about 3.6 meters . A gravity survey is conducted on the earth's surface above the cave along a profile trending east west, with spacing interval of 3 meters (Al-Banna 1996). The present method is applied for the measured gravity profile,assuming the cave as a spherical body, and the depth found to be equal to 3.35 meters, (Fig.14).The obtained depth is nearly confirm the actual depth to the center of the cave measured by Al-Banna (1996).

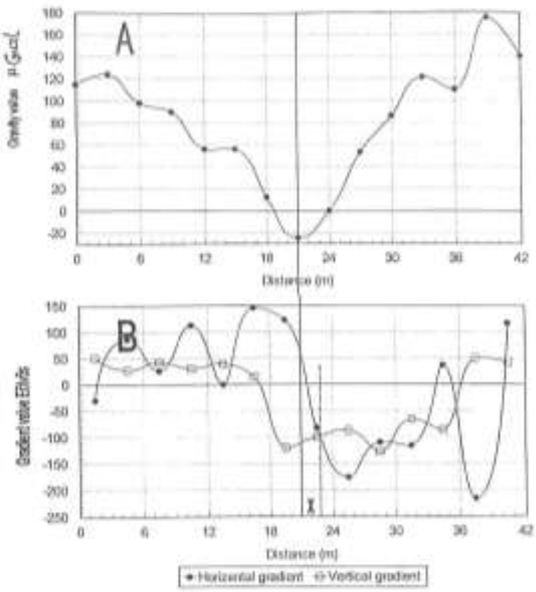


Figure (14): A- Bouguer anomaly profile trending East-West over a known cavity at Rawa area, Al-Anbar province, west Iraq.
B- The Horizontal and Vertical gradients of the cavity of Rawa area, showing the distance of the nearest intersection point from the centrel anomaly (x), which is equal (1.9m).

2. West Senegal (Louga area) anomaly:

A gravity and magnetic survey are conducted in west Senegal in order to define the sedimentary basin (Nettelton 1962). A north-south gravity anomaly profile crossing the gravity map of west Senegal (west Africa) with length 25 kilometers through Louga area is considered for estimating the depth to the gravity source by Abdelrahman and Al-Araby (1993). They used the least square minimization approach to determine the depth, which was found to be equal to 9.29 kilometers. The basement depth at Louga area was found from the aeromagnetic data interpretation equal to 4.15 km. The present method is applied for the gravity profiles that passing through Louga area. Due to the shape of the anomaly the source is approximated to a horizontal cylinder body. The obtained depth of the source is about 3.94 kilometers, which confirms the basement depth obtained from the aeromagnetic data, (Fig.15). The relatively high value of depth obtained by Abdelrahman and Al-Araby may be present the maximum depth,while present method dealing with the center of mass.

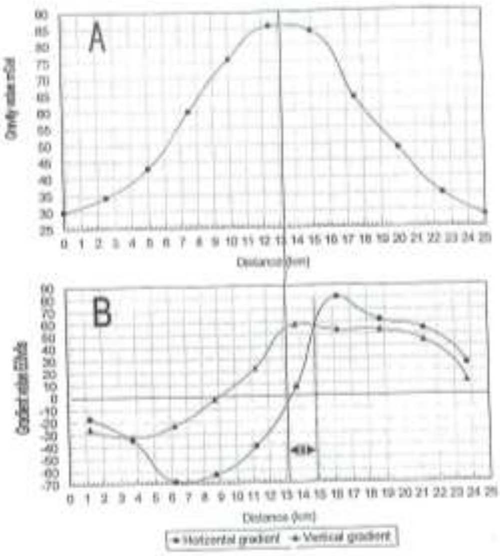
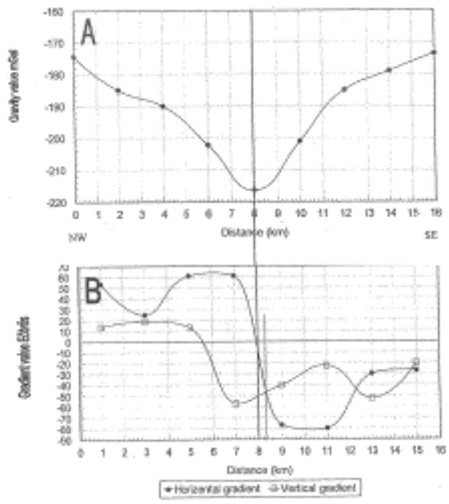


Figure (15): A- North - South gravity profile of 25 km over the louga area, West Senegal, West Africa, (Nettelton 1962).
B- Horizontal and Vertical gradients of the gravity profile of Louga area. The distance of the nearest intersection point to the central axis of the anomaly (x), is equal (1.65 km).

3. Dry Lake Valley anomaly:

Dry lake valley gravity anomaly is located in central Lincoln County, Nevada, and oriented with its long axis in north-south direction (Butler 1995). The dry lake valley exhibits basin and range structure, with the valley occurring above a graben between two high angles of normal basement faults, on both sides of the valley(Butler 1995). McLemore and Walen (1979), use an interactive 3-D gravity inversion program to determine the subsurface model of the gravity field. The obtained model, which is constrained by seismic refraction results, show that the depth to the center of deepest part along the profile AA$^-$, crossing the valley in NW-SE direction, is about 1 km. Butler (1995) used the gradient analysis procedure in order to interpret the gravity profile AA$^-$. He predicated that the depth of the center of the source at the deepest part of the valley is 2.7 kilometers.

The present method has been applied to the gravity profile AA$^-$ in order to estimate the depth to the source, (Fig.16). Considering the source as a horizontal cylinder the depth found to be equal to 0.83 kilometer. Which is nearly confirming the result of the 3-D gravity model. The high depth value obtained by Butler is due to the procedure of gradient analysis itself as mentioned in the introduction.



Figure(16):A-The Bouguer anomaly profile a crossing the gravity anomaly of Dry Lake valley in northwest-southeast direction. The gravity anomaly of Dry Lake valley located in central Lincoln County,Nevada. This anomaly is oriented with its long axis north-south (Butler, 1995)
B- The horizontal and Vertical gradients of the profile a crossing the gravity anomaly of Dry Lake valley. The nearest intersection of gradient profiles to the central axis of the gravity anomaly is shown to be fare by a distance (x)= 0.35 km.

4. Bokaro coalfield anomaly:

Bokaro coalfield is elongated structure of east-west direction in Damodar valley in eastern India. Gravity studies show that the structure consists of three separated basins. These basins have a typical graben type structures. An interpretation of the gravity profile CC$^-$ a cross the central gravity low, assuming two-dimensional model, suggests that the thickness of the sediment is close to 5 kilometers, (Verma et al 1987). These results mean that the depth to the center of basin is 2.5 kilometers.

The present method has been applied to the gravity data along the profile CC$^-$ and the depth to the center of the basin found to equal 2.40 kilometers (Fig. 17).

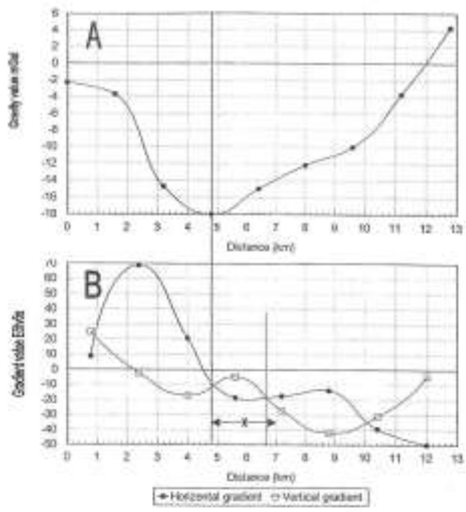


Figure (17): A- The Bouguer anomaly profile a cross the central part of Bokaro cool field, North Karanpura India (After Verma. Et al 1987).
B- Horizontal and Vertical gradients of the Bouguer anomaly profile of Bakuro cool field. The distance between the nearest intersection point to the central axis of the anomaly (x), which is equal (1.87 km).

Table (1) summarizes the results of applying the present method for the four considered anomalies. It is obtained from the studied cases that the actual depth is always greater than that depth obtained using the present method.

Table (1): Results of application of the new approach on the well known depth cases. Distance (x) as defined in the figures.

Tested case	Distance (x)	The considered geometrical body	Estimated depth	Actual depth	Percentage of error	Reference and remarks
1. Rawa cave Iraq	1.9m	Sphere	3.37m	3.6m	6%	Al-Banna (1996) (depth to the center of cave)
2.West Senegal West Africa (Louga area)	1.65km	Horizontal cylinder	3.94km	4.15km	5%	Nettleton (1962) Depth to the basement
3.dry lake valley Nevada USA	0.35km	Horizontal cylinder	0.86km	1km	14%	Butler (1995) depth to the center of source from 3-dimensional gravity interpretation
4.Bakaro coalfield India	1.87km	Horizontal cylinder	4.46km	5.0km	12%	Verma et al (1987), depth to the basement

Applications to unknown depth cases

The present method has been used to estimate the depth of source of two gravity anomalies in Iraq. These gravity anomalies are observed on the unified gravity anomaly map of Iraq, which is prepared by Abbas et al. (1984).
These anomalies are:

1.North Nasiriya gravity anomaly:

North Nasiriya is a large negative gravity anomaly, which is nearly circular in shape with diameter of about 60 kilometers. This anomaly is situated north Al-Nasiriya City, south of Iraq. An east-west gravity profile is considered to applying the present method and estimating the depth of the gravity source. The horizontal gradient is determined using spacing interval of 5 kilometers. The vertical gradient is determined using Hilbert transform,(Fig.18). The source considered being spherical in shape. Depth of the gravity source center is found to be equal to 36.2 kilometers. Which means that the source center is within the lower part of the crust. The large diameter of the gravity anomaly and large depth seems that the source may be related to a batholith body. The batholith body may be extended in lateral dimension, with limited thikness.

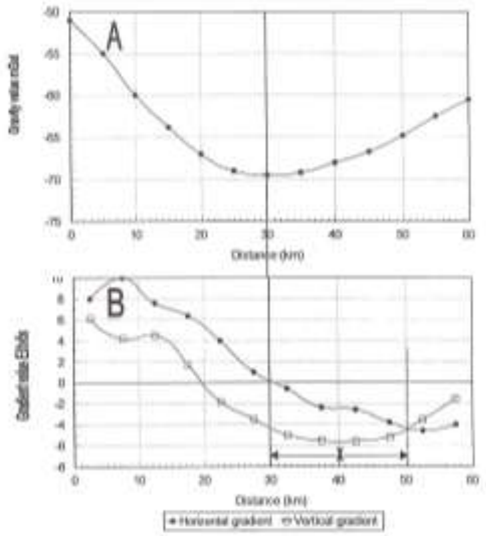


Figure (18): A- showing an E-W profile crossing north Nasiriya negative gravity anomaly.
B- the Horizontal and Vertical gradients of the East- West profile that is crossing the north Nasiriya negative gravity anomaly. This figure showing the intersection point between both gradients and its relation to the center of the anomaly x=20.5 km .

2.North Hemrin anomaly:

The north Fadhal dome, which is the part of north Hemrin structural feature, is situated at the northern part of Iraq. This structure is elongated in the northwest-southeast direction. A gravity profile crossing the structure perpendicularly is considered to determine the depth of the source. The horizontal and vertical gradient of this profile is determined with various spacing intervals 1,2,3 kilometers, (Fig.1). The gravity source approximated to a horizontal cylindrical body. The obtained depth of the source using the suggested method is equal to 4.77 kilometers. As the basement depth is estimated from the aeromagnetic data, using the inflection tangent intersect method, in the studied area equal to 9.4 kilometers C.G.G. (1974), the gravity source considered to be within the sedimentary cover.

Conclusions

The horizontal and vertical gradients of gravity anomaly are considered in the present study to estimate the depth to the gravity source. It is concluded that the distance between the nearest intersection point, of the gradient profiles, and the center of the anomaly is related to the depth of the source. Two relations for sources approximated to spherical and horizontal cylinder bodies are obtained.These releations can be applied after approximating the gravity anomaly to a sutaible geometerical body (sphere or horizontal cylinder. The suggested method has been applied for determining the source depth of four well known depth cases, the result of present method are acceptable with error ranged between 5% to 14% in depth estimation. The considered cases show that the estimated depth is always less than the actual depth, this may be due to considering the gravity anomaly with out smoothing (befor seperating local from regional anomaly) .

Two gravity anomalies from the gravity map of Iraq are used for applying the present method for source depth estimation. It is found that the source of north Nasiriya gravity anomaly is within the lower part of the crust, while the source of north Hemrin gravity anomaly is found be with the sedimentary cover.

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استخدام تقنية النحدار لتخمين اعماق مصادر الثاثير الجذبي

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[٢]قسم علوم الارض التطبيقية، كلية العلوم، جامعة تكريت، تكريت، جمهورية العراق

الملخص:

في هذه الطريقة الجديدة تم الاعتماد ةعلى الانحدار الافقي والعمودي للبيانات الجذبية لتخمين عمق مصادر التاثير الجذبي، تبين ان المسافة لاقرب نقطة تقاطع للانحدار الافقي والعمودي الى المحور المركزي للشذوذ الجذبي (x) ترتبط بشكل مباشر بعمق مصدر التاثير الجذبي. تم الحصول على علاقتين لتخمين عمق المصدر الجذبي بعد تقريب شكل جسم المصدر من الكره او الاسطوانة الافقية. تم تطبيق الطريقة المقترحة على اربع مجاميع من البيانات الجذبية الخاصة بمصادر شذوذ جذبي معلومة العمق حيث ان النتائج المحسوبة بهذه الطريقة بدت مقاربة للاعماق الحقيقية. كما تم تطبيق الطريقة لحساب اعماق الشذوذ الجذبي المجهولة في منطقتين في العراق، وتم اعتماد هذه النتائج للاعماق المحسوبة.