World Applied Sciences Journal 6 (3): 393-400, 2009
ISSN 1818-4952

Normalized Full Gradient of Gravity Anomaly Method and Its Application to the Mobrun Sulfide Body, Canada

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Abstract: Gravity anomalies are sensitive to variations in size, depth and composition of anomalous sources. A suitable approach to detect and estimate spatial locations and depth is the Normalized Full Gradient (NFG) method. The NFG in cross-section or maps manifest clearly the depth of the centers or top of the anomalous bodies at certain harmonic numbers. The obtained results from synthetic data, with and without random noise, show closed maxima on an NFG map that indicate the spatial locations of the centers and depth of the causative bodies. Modeling studies show that the estimated depth largely depends on the harmonic number used to calculate the NFG, which are closely related to the profile lengths and gravity griding intervals. In this study, the NFG method is applied to Mobrun sulfide body in Canada for estimating the depth to the top of it. The NFG closed maxima alongside the borehole data, shows that the Mobrun ore body is located in shallow depths, about 17 meters and extended to 175 meters, approximately.

Key words: Gravity . Analytical downward continuation . Normalized full gradient (NFG) . Synthetic gravity model . Mobrun sulfide body

INTRODUCTION

There are numerous methods that have been developed to delineate gravity anomalous bodies and indicate their locations and depths from the potential field. Because the detection objectives are finding small bodies at depths hosted by larger structures, the methods can be laid of high pass filter such as derivative calculations to enhance potential anomalous due to small bodies and analytical downward continuation to enhance gravity effects due to bodies at depths.

Analytical downward continuation is a method to estimate the field closer to the source and consequently results in a better resolution of underground rock distribution. However, the usefulness of this process is limited by the fact that the operation is extremely sensitive to noise. Once downward-continuation is fulfilled, a signal is amplified exponentially, with an exponent proportional to the spectral frequency. With noise free data, downward continuation is well defined, we do not attempt to continue below the source level [1]. In the presence of noise, the amplification of high frequencies is so strong that it quickly masks the information in the original profile. Low-pass Fourier filtering, while suppressing such noise, also blurs the signal, overcoming the purpose of sharpening by downward continuation.

Despite the above-mentioned problems, most geophysical experts have long been interested in this technique because of its importance to the mineral exploration. Furthermore, this method is fast and cheap way to determine the initial depth of the subsurface features, especially where there is no other geophysical or well-logging data. A good analytical downward continuation process could provide subsurface general images, allowing an enhanced interpretation. Also, analytical downward continuation has the ability to determine accurately both horizontal and vertical extents of geological sources [2].

In this study, the authors estimating spatial locations and depths of the anomalous bodies by using Normalized Full Gradient (NFG) method, which uses vertical and horizontal derivatives of the observed gravity anomaly in order to analytical downward continuation. The method was proposed in the middle of 1960s [3, 4] and was successfully used in determination of singular points in potential field

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methods [5-8]. The NFG method has also been widely used in separation of anomalies with certain structures by analytical downward continuation in gravity method [9-11]. Also, this method was applied to magnetic data to hydrocarbon reservoir [12] and identify locations of anomalous bodies in Ojatabad iron deposit [13].

In this paper, 2D and 3D NFG of gravity anomalies caused by subsurface bodies at datum are presented. The applicability of the method is illustrated on gravity data due to synthetic models. Furthermore, the practical utility of the method is demonstrated to interpret the observed gravity anomalies over the Mobrun sulfide body, Canada.

MATERIALS AND METHODS

The basic concept of the NFG method is a kind of downward continuation of the normalized full gradient of gravity anomaly. Instead of gravity anomaly itself, the NFG uses its transformed components that eliminate oscillations which occur near or under the anomaly source in expedient downward continuation. Therefore it is possible to calculate the downward continuation in the area hosting the bodies. Two-dimensional NFG of gravity anomalies [14, 15] is defined as:

$$G_N(x_i, z_k) = \frac{\sqrt{\left(\frac{\partial g(x_i,z_k)}{\partial x}\right)^2 + \left(\frac{\partial g(x_i,z_k)}{\partial z}\right)^2}}{\frac{1}{M}\sum_{i=0}^{M}\sqrt{\left(\frac{\partial g(x_i,z_k)}{\partial x}\right)^2 + \left(\frac{\partial g(x_i,z_k)}{\partial z}\right)^2}} \tag{1}$$

where, $k = 0, dz, 2dz, 3dz, \ldots, z$, $g(x_i, z_k)$ is gravity anomaly along the x-axis, M is the number of observation points at the profile, $\partial g(x_i,z_k)/\partial x$ and $\partial g(x_i,z_k)/\partial z$ are derivatives of $g(x_i, z_k)$ along x and z directions, respectively and dz is the interval between the levels for down-warding continuation.

The NFG of gravity anomalies is calculated using the Fourier series in such a way that the $g(x, z)$ function along the x-axis can be expressed as the summation of sine and cosine functions [16, 17]. Gravity anomalies g(x, z) over the range (0,L) can be expressed by infinite Fourier sine series [18]. In order to downward continuation process in the wave-number domain using a Fourier series summation multiply with an exponential function that is described by Jung [19] as follows:

$$g(x,z) = \sum_{n=1}^{N}\left[B_n \mathrm{Sin}\left(\frac{\pi n}{L}\right)x\right]\exp\left(\frac{\pi n}{L}z\right) \tag{2}$$

where L stands for integral interval or length of gravity profile, z is the plane on which the downward continuation is preformed, B_n is the Fourier sine coefficients and n is the harmonic. The Fourier coefficients can be calculated using several methods such as trapeze formula and Filon method [20]. Here, Fourier coefficients are calculated by using the Filon method [21].

By considering the zero values at the borders of the profile of function $\Delta g(x,0)$ the B_n coefficients [20, 21] are given by the equation

$$B_n = \frac{1}{M-1}\left\{\begin{array}{l}\beta\sum_{i=0}^{M-1} g(i)\sin\frac{\pi n}{2(M-1)} + \\ \frac{\gamma}{2}\sum_{i=1}^{M-1}[g(i)+g(i+1)]\sin\frac{\pi n}{2(M-1)}(2i+1)\end{array}\right\} \tag{3}$$

Where

$$\beta = \frac{2}{\alpha^2}[1+\cos^2\alpha] - \frac{2}{\alpha^3}\sin 2\alpha\},$$

$$\gamma = \frac{4}{\alpha^3}[\sin\alpha - \alpha\cos\alpha],\ \alpha = \frac{\pi n}{2(M-1)}$$

In order to eliminate high frequency noise and the Gibbs effect due to downward continuation and to increase stability the sine expansion coefficient, equation (2) is multiplied by a smooth factor [9-11, 13].

$$Q_n = \left[\frac{\mathrm{Sin}\left(\frac{\pi n}{N}\right)}{\frac{\pi n}{N}}\right]^{\mu} \tag{4}$$

where μ is a constant known as the degree of smoothing which controls the curvature of the Q_n function and it can be any integer number. In this paper, we take 2 as the integer, which gives reasonable results in the downward continuation [13, 21, 22]. The Q_n function is known as Lanczos smoothing term, which was used originally by Berezkin [4] to eliminate the Gibbs effect. Normalization of the full gradient of the gravity anomaly helps minimize the problems associated with downward continuation of gravity anomalies, such as strong, high-frequency oscillations. Then;

$$g(x,z) = \sum_{n=1}^{N} B_n \mathrm{Sin}\left(\frac{\pi n}{L}x\right)\exp\left(\frac{\pi n}{L}z\right)Q_n \tag{5}$$

In fact, most of the geological structures are three-dimensional; therefore, the NFG in 3D gives more reasonable results. 3D NFG of gravity anomalies [9, 10] can be calculated by:

$$G(x_i, y_j, z_k) = \sqrt{\left(\frac{\partial g(x_i, y_j, z_k)}{\partial x}\right)^2 + \left(\frac{\partial g(x_i, y_j, z_k)}{\partial y}\right)^2 + \left(\frac{\partial g(x_i, y_j, z_k)}{\partial z}\right)^2}$$

$$G_N(x_i, y_j, z_k) = \frac{G(x_i, y_j, z_k)}{\frac{1}{M}\sum_{i=1}^{p}\sum_{j=1}^{q} G(x_i, y_j, z_k)} \quad k = 0, dz, 2dz, \ldots, z \quad (6)$$

where, $g(x_i, y_i, z_k)$ is gravity anomaly over an area, $M = p \times q$ is the number of observation points over an area, $\partial g(x_i, y_j, z_k)/\partial x$, $\partial g(x_i, y_j, z_k)/\partial y$ and $\partial g(x_i, y_j, z_k)/\partial z$ are derivatives of $g(x_i, y_j, z_k)$ along x, y and z directions, respectively, $G(x_i, y_j, z_k)$ is full gradient of gravity anomaly and dz is the interval between the levels for down-warding continuation. Equation (6) can be used to calculate the $G_N(x_i, y_j, z_k)$ at different z levels. The spatial distribution of the NFG of gravity anomalies on certain planes can be calculated and analyzed.

SYNTHETIC MODEL

In order to test the effect of the NFG method in detecting anomalous bodies and estimating the depths of them, the method was applied to two numbers of synthetic gravity anomalies (sphere and vertical cylinder). For two models, the profile length is chosen as 20 and 10 km respectively, the structural locations of the models correspond to the midpoints of the profiles.

The gravity anomaly of a sphere model [17] is given by:

$$\Delta g_z = \frac{4\pi G \Delta\rho . R^3}{3} \times \frac{z}{\sqrt{(x^2 + y^2 + z^2)^3}} \quad (7)$$

where R=radius of sphere, x and y are horizontal distances from the centre at x-axis and at y-axis, respectively and z=depth of sphere (Fig. 1).

In order to calculate the gravitational attraction of anomalous bodies on a point that lies away from the symmetry axis the authors use series in term of spherical functions [23]. In the simple way, the gravity effect of a finite vertical cylinder is given by Hammer [24] and Nettleton [25] as:

$$g(x, y, z_t, z_b) = \pi G \rho R^2 \left(\frac{1}{\sqrt{x^2 + y^2 + z_t^2}} - \frac{1}{\sqrt{x^2 + y^2 + z_b^2}}\right), \quad (8)$$

where x and y are the horizontal positions coordinates, z_t is the depth to the top, $z_b = z_t + L$ is the depth to the base, G is the gravitational constant, R is the radius of the cylinder and ρ is the density contrast (Fig. 1). Another way to calculate the vertical gravity effect of a vertical cylinder at an arbitrary point is Talwani method [26, 27]. The Matlab program uses the Talwani's theory and produces the synthetic gravity profile on which the NFG method was carried out.

In all of the published papers, number of harmonic (N) was generally determined by trial-and-error method and use additional data such as drilling data, depends on the conditions of the problem and the characteristics of the data. In this method, several values in increasing order are tried to determine N (N=M/2), lower limit of N is set to 1 [9-11, 21].

To overcome the drawbacks of trial-and-error methods, here we proposed a new method based on variation of NFG and harmonic number to find the optimum number. In the method, the optimum harmonic number for estimating the depths of the bodies is very important. The maximum of NFG value using harmonic numbers (N=1-100) has been calculated and variations of the NFG versus N is drawn (Fig. 2).

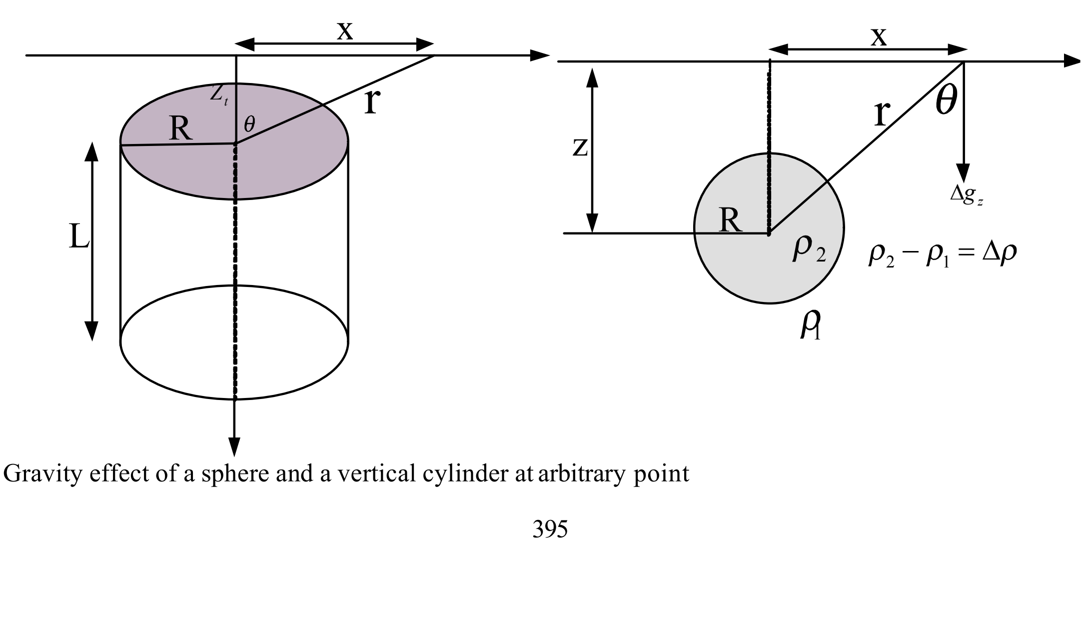

Fig. 1: Gravity effect of a sphere and a vertical cylinder at arbitrary point

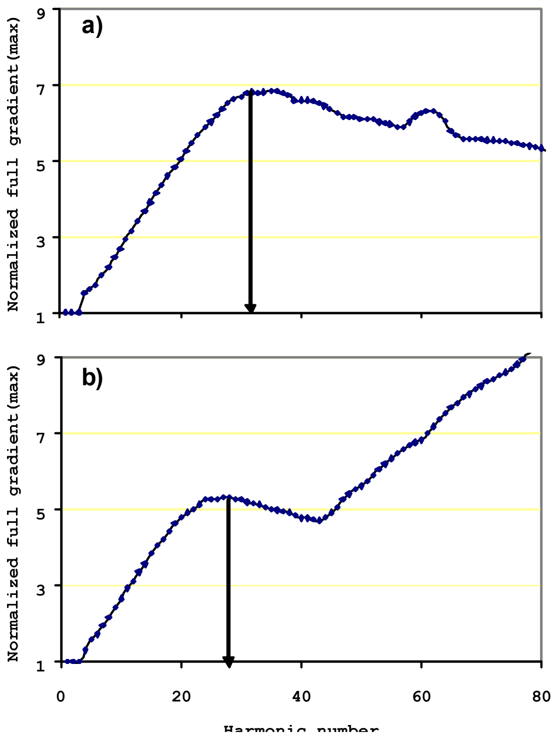

Fig. 2: Relationship between N and the NFG (max), a) for sphere: N_{opt} = 32, b) for vertical cylinder: N_{opt} = 27

According to the obtained results, the first relational maximum which produced by harmonic numbers, will be considered as the optimum harmonic number. On the other hand, the NFG cross section with selected optimum harmonic number shows the depths and horizontal locations of anomalous bodies.

The NFG method with different harmonic numbers is applied to the synthetic anomalies of a sphere model with density contrast $\Delta\rho = 0.1 g/cm^3$ and z=2 km (Fig. 3a). It is observed that the method produces closed contours around the anomalous body for all harmonic numbers. The results of this study have shown that the center of the fully closed contours belonging to NFG harmonics corresponds to the actual burial depth of the sphere. Therefore, the depth of the sphere model (2 km) is visually identified from the maximal enclosure location [13, 14] for N=32 harmonic number (Fig. 3b).

Also, the NFG method is performed for the simple vertical cylindrical model at various harmonic numbers. The method is applied to a cylindrical model with density contrast $\Delta\rho = 0.1 g/cm^3$ and z=1 km depth to top and the results are given in Fig. 3c. Although the surface location of the vertical cylindrical is determined by NFG at all harmonic numbers, the depth to top of the vertical cylindrical identified by NFG sections at N=27 (Fig. 3d).

APPLICATION TO THE FIELD EXAMPLE

Here, the NFG method has been applied to gravity anomaly over the Mobrun sulfide body in Noranda, Quebec, Canada. The gravity map is shown on Figure (4). The A-B profile has been designed at interval of 5.28m on gravity map (Fig. 5). Elliptical contours in the gravity map indicate a 2.5D source geometry which, in the present context, can be interpreted as either a 2D or 3D source [29]. Mineralization zone and the location of sulfide body have been determined by some explorative boreholes. According to drilling data and geophysical interpretation in Noranda, the depth of the top of the body is about 17m and extended to 187m [28-30]. In this area, the original gravity survey has been done on 60m spaced lines with stations in every 30m. The gravity map with contour interval of 0.05mGal is used for calculating NFG. All computations were performed with a grid of 5×5m spacing. The range of the gravity anomalies is within -1.0 to +1.7 mGal.

The NFG of gravity anomalies (Fig. 6) is closely related to the number of harmonic Fourier series. Determining an optimum value of N is of significant importance. To obtain the optimum N, the NFG values of gravity anomalies are calculated for several Ns at the A-B profile that perpendicular to the long-direction of gravity anomaly. In the calculating process, the N equal to 44 is selected as the optimum harmonic number (Fig. 7). If N is equal to 44, the maximum of the NFG of gravity anomalies shows that depth to the top of the body is about 17 m (Fig. 6). These results are suitable with the drilling data.

3D-NFG of gravity anomalies of Mobrun: In the Mobrun area, the authors only concentrate to potential mineralized areas with depth up to 60m. The 3D NFG of gravity anomalies is calculated from equation (6). We calculated the NFG of gravity anomaly, at the depth levels of 15, 25, 35, 45, 55 and 56m. The optimum coefficient, N=44, is applied for all depth levels mentioned above. In this case, the closed maxima of the NFG of gravity anomalies show an existence of the density excess anomalies that closely related to the possible ore body. Figure 8a-8f shows clearly that the spatial distribution of the maxima of the NFG of gravity anomalies depend on the depth of investigation. In other words, it is caused by the spatial variation of the rock density of subsurface geological formations. In this case, at deeper depths (more than 60m), because of small dimension of measuring area, the closed maxima are not clear as like as shallow depth. A comparison between the calculated results and borehole data has shown out a close correlation. Almost of the known ore body discovered

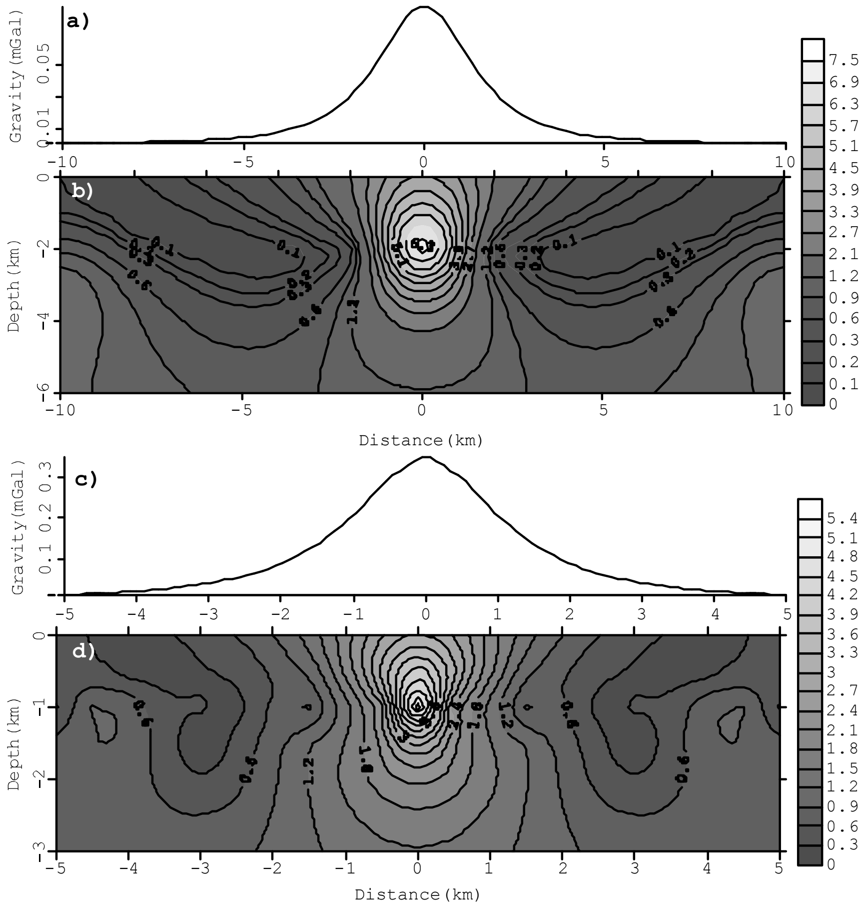

Fig. 3: a) gravity anomaly of a buried sphere at z=2 km, ρ=0.1 g/cm^3, R=0.5 km, L=20 km, dx=0.5 km, b) Normalized full gradient of gravity anomaly due to the sphere. c) gravity anomaly of a buried vertical cylinder at depth to top is 1 km, ρ=0.1 g/cm^3, R=0.5 km, L=10 km, dx=0.5 km, d) Normalized full gradient of gravity anomaly due to the vertical cylinder

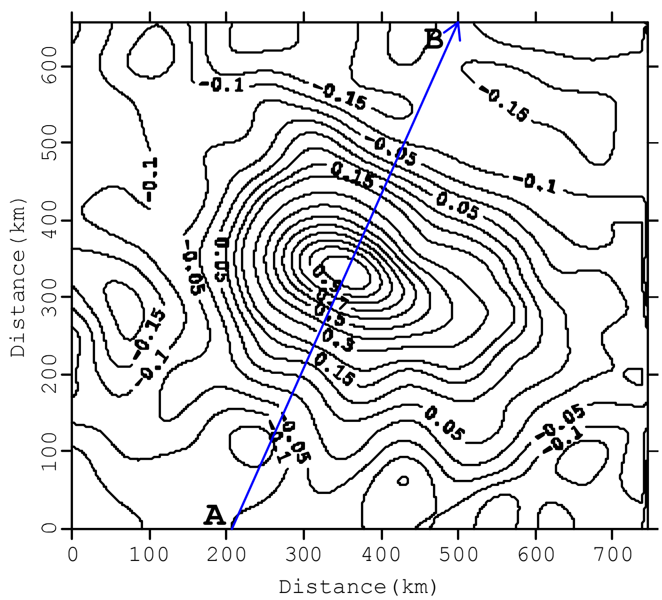

Fig. 4: showing gravity anomaly due to Mobrun sulfide body and location of A-B profile

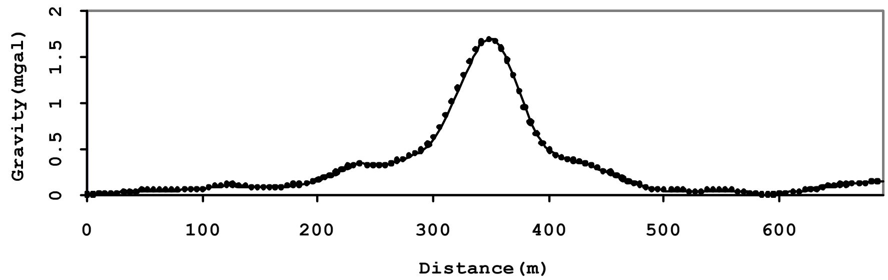

Fig. 5: Gravity anomalies on A-B profile

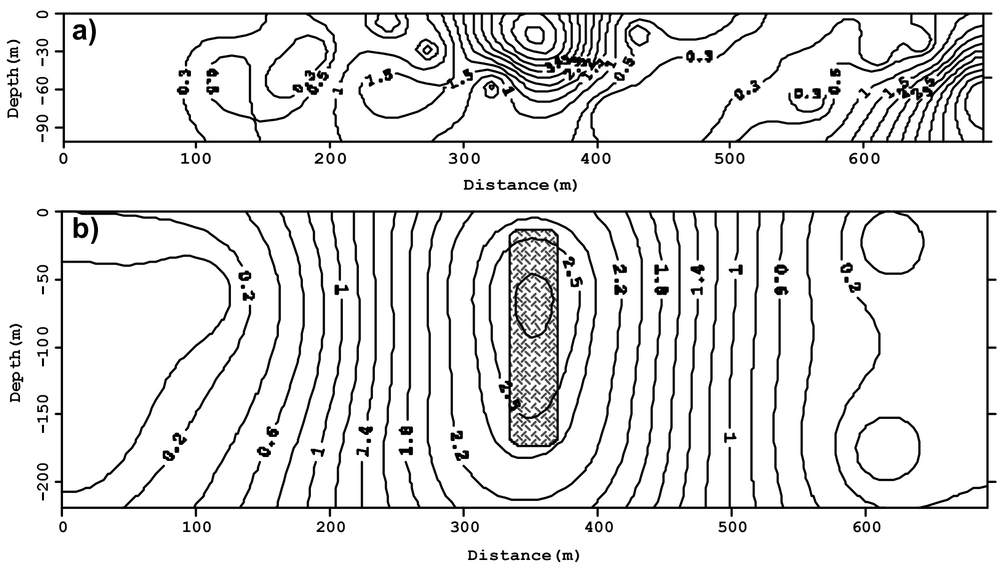

Fig. 6: a) NFG on cross-section A-B (N=44), b) NFG on cross-section at A-B (N=10)

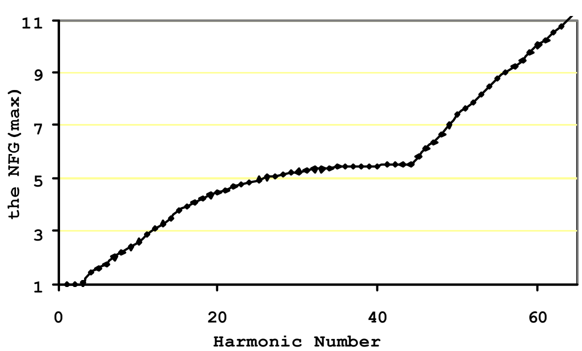

Fig. 7: Relationship between N and the NFG (max), Nopt=44

by drilling data are related with the maxima of the NFG of gravity anomalies.

CONCLUSIONS

Application of normalized full gradient of gravity anomalies allows to eliminate the fictitious sources and detect the singular points related to anomalous bodies. Because this method uses the Fourier series coefficient for calculating the NFG value, so the main problem is determining the optimum harmonic number N. The obtained results show that it could estimate the optimum harmonic number without the other primary data such as drilling. Density variations which are caused by the presence of ore body make the maximum closure for the reservoir. The results that obtained by the NFG method to Mobrun sulfide body in Noranda, Quebec, Canada have shown that the NFG method could be used effectively for mineral exploration. This method has shown that the NFG are reliable in detecting and locating density anomalies associated with possible resources. It can be used to estimate depth to the top and base and define shape of the anomalous bodies and locate explorative boreholes. To increase the feasibility in detecting and locating promising mineral areas from gravity data, the effect of regional gravity must be removed.

ACKNOWLEDGEMENTS

The authors thank Dr. Mark Pilkington from Geological Survey of Canada for providing the Mobrun sulfide gravity data.

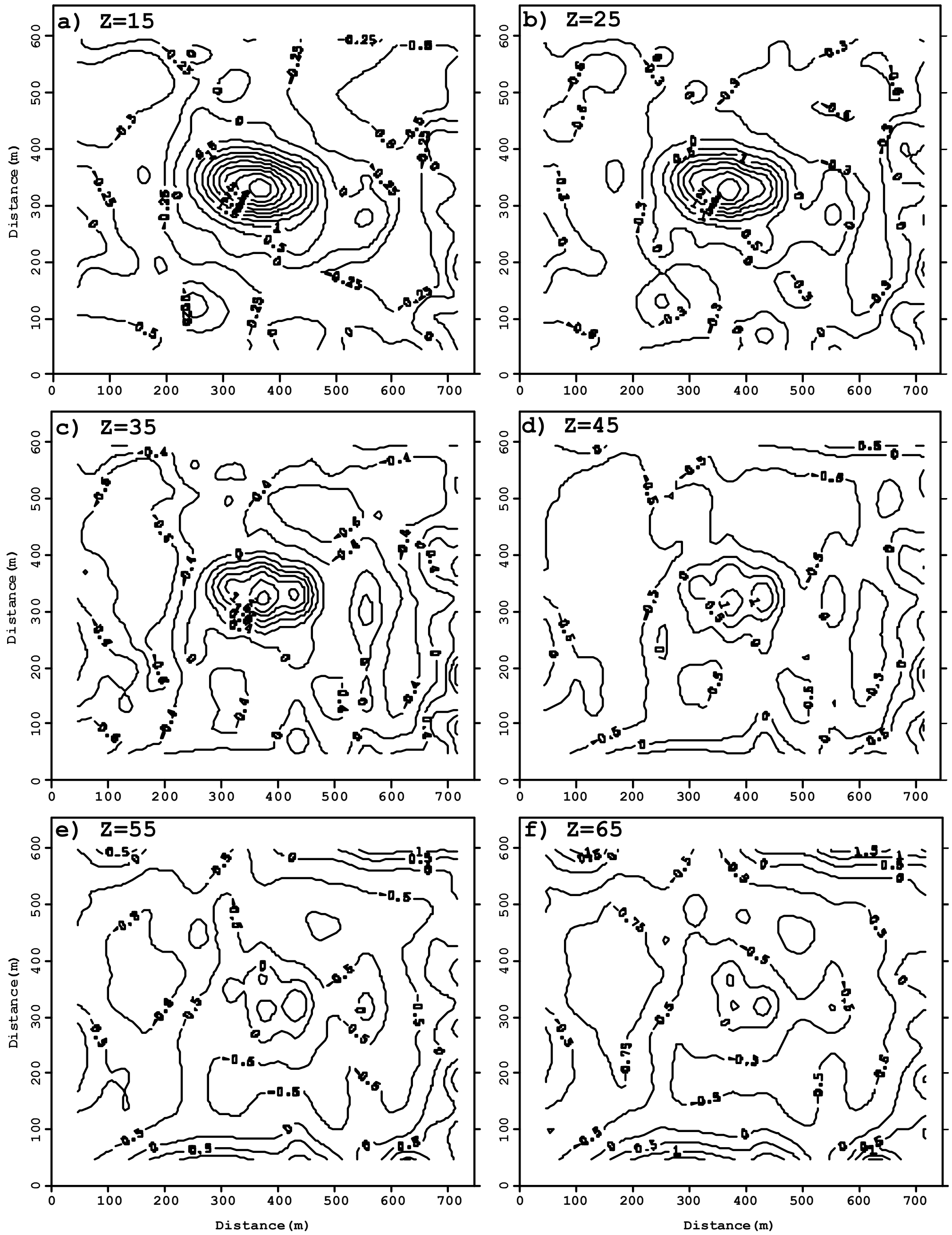

Fig. 8: The NFG of gravity anomalies at different depths in 15, 25, 35, 45, 55 and 65 m

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