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A Procedure to Correct Errors in Depth Estimation from Slope Hale Slope Method

Fitian R. Al-Rawi and Ali M. Al-Rahim*

Department of Geology, College of Science, Baghdad University, Iraq,
**Email: alial_rahim@yahoo.com.*

أسلوب لتصحيح الأخطاء عند تقدير العمق باستخدام طريقة الميل ونصف الميل

فتيان رشيد الراوي و علي مكي الرحيم

خلاصة: جرى تحري لتقدير النسبة المئوية للأخطاء المحتملة عند حساب عمق المصدر المسبب للمجال المغناطيسي عند خطوط عرض مختلفة باستخدام طريقة الميل ونصف الميل المبتكرة والتي اقترحها بيترز في عام 1949. استخدمت مجموعة من النماذج المتمثلة بالقواطع السميكة التي لها أعماق وزوايا ميل مغناطيسي مختلفة (من صفر إلى 90 درجة) لحساب النسبة المئوية للأخطاء مع القيم المختلفة للميل وقد عرض أسلوب لتصحيح هذه الأخطاء في تقدير العمق. تتراوح النسبة المئوية المحسوبة بين قيم موجبة وسالبة لنفس زاوية الميل عند الأعماق المختلفة وهذه قد خلقت صعوبات لوضع صيغة تخص العامل المستخدم لتعديل قيم الأعماق المقدرة ومن ثم التغلب على هذه المشكلة. لقد وجدت علاقة بين المسافة الأفقية عند نقطة التماس ومركز أقصى ميل مع الأعماق الحقيقية والمحسوبة. تم رسم خطين مستقيمين من هذه العلاقة وقد تقاطعت في نقطة معينة لكل زاوية ميل. يحدد موقع نقطة التقاطع الفرق بين القيم الحقيقية والمحسوبة وهذا أما يضاف أو يطرح من العمق المحسوب للحصول على العمق الحقيقي. وفي حالة حساب العمق للمصدر في العمل الحقيقي فان مقدار قيمة التصحيح سوف تقدر من خلال تحديد نقطة التقاطع بين العمق المحسوب والمسافة الأفقية ومن ثم يحسب الفرق عن الخط المائل للعمق الحقيقي المخصص لزاوية الميل. إن كل زاوية ميل لها علاقتها الخاصة المتمثلة بالخط المائل وان نقطة التقاطع تستخدم لتقدير العمق الحقيقي.

ABSTRACT: The novel method named slope half slope for depth estimation of the causative magnetic field proposed by Peters (1949) has been investigated to determine the possible percent errors in depth estimation to magnetic sources situated at different latitudes. A sequence of models represented by thick dykes with various depths and with different values of field inclination (0 to 90°) has been used to estimate the percentage errors for the different inclination values. A procedure to correct the errors in depth estimate has been discussed. The calculated percent errors range between positive and negative values for the same angle of inclination at various depths. This raises difficulties to use a formula concerning the factor to adjust the estimated depths and to overcome this problem. Therefore, a new approach has been adopted to correct the estimated depth values. A relationship between the horizontal distance at the tangential point and center of the maximum slope with the actual and estimated depths is found. Two straight lines are plotted from this relation and they are intersected at a certain point for each inclination value. The location of this point defines whether the difference between the actual and the estimated depth values will be added to or subtracted from the estimated depth to get the actual depth. In real depth determination, the correct value is determined by defining the intersect point between the estimated depth and the horizontal distance and then calculating the difference from the actual slope line for the assigned inclination angle. Each inclination angle has its own relation and intersected point that can be used to determine the actual depth.

KEYWORDS: Magnetic depth estimation, slope method, correction procedure, percent errors in depth estimation, percent errors with inclinations.

1. Introduction

Much is written on the variety and relative merit of methods for estimating the depth to the source of magnetic anomalies. Since the magnetometer is primarily a tool for subsurface mapping and detection, it follows that determination of the depth as well as edges of bodies is important in its application to geological exploration and search. Several methods have been developed to estimate the magnetic depth (Reynolds 1998, Telford *et a1*. 1990). The number keeps growing with continual development of new algorithms (Li. 2003). In most cases, depth may be estimated by visual inspection. Several rules of thumb, modeling (i.e. calculation of assumed source and comparison with observation, Gay, 1963, Stanley, 1977), measured gradient techniques (Naudy, 1971, Atchuta *et al*. 1981, Ku and Sharp, 1983), spectral analysis techniques (Spector and Grant, 1970, Bhattacharya, 1971) and various computer -oriented pr ocedures (Thompson, 1 982), have been used.

A given anomaly could have an infinite number of possible sources and source depths, but the realistic models that are assumed usually produce maximum depth estimates. Riddel (1975) has summarized the results of applying the various empirical relations given by half width rule method, Peters rule, Tiburg rule, Hannel rule, Thalen rule and slope distance rule. He stated that Peters rule gave the calculated heights above the ore body that agree reasonably well with the nominal terrain clearances. The subject of depth estimation for magnetic sources has been discussed recently by Li (2003).

The shape of the magnetic anomaly has a relation to the depth between the level of measurements and source. This property enables one to determine the approximate depth to the source independent of any other information concerning the source. The characteristic of anomaly wavelength, or width, as a function of depth will allow rapid and easy interpretation of anomalies of interest.

Peters' slope half-slope method (Peters, 1949) is one of the earliest magnetic estimate technique. The method depends on the horizontal distance between two parallel lines that pass through the maximum and minimum of an anomaly and have a slope equal to one half the maximum horizontal gradient of the anomaly. The depth to the top of the body is proportional to the horizontal distance. Each of these horizontal distance measurements when multiplied by an empirical-determined factor equals the depth to the top of the anomaly source. The slope is multiplied by a factor between 0.5 and 1.5 depending upon whether the source is a thin or thick dyke. The slope method is a "direct" estimate that is roughly proportional to depth (Breiner, 1994). This method was improved by the Bean ratio method (Bean, 1966) by introducing a regional slope thus removing the effect of a local regional field.

The depth estimates derived from any of the techniques described are seldom more accurate than 10 percent of the actual depths and sometimes as poor as 50 percent (Breiner, 1994). In theory, most of the estimates are maximum estimates so that the real source will actually be at a shallower depth.

Although Peters' method was published in 1949, it is still being used because the relation between depth and slope of the anomaly is easy to perform. The problem in the application of such empirical relation is the factor value that should be used and the role of inclination angle of the magnetic field i.e. at what latitude are the magnetic measurements carried out. The purpose of the present paper is to determine the percentage errors in depth estimation by applying this method and to overcome this problem by adopting a new proposed and applicable treatment procedure for different inclination angles as a correction to the estimated depths.

2. Percentage errors in depth estimation

The procedure followed in the calculation of the percentage error is through using models of thick dykes, having various depth values at every 10 degrees of magnetic inclination and with constant other parameters, in addition to inclination of 45°. These angles give the effect of inclination angle on the shape of the magnetic anomaly from the equator to the North Pole (Figure 1). Calculations are based on a ready used computer program issued by Geophysical Software Solution Pty. Ltd-Pdyke copyright 2002-2005. Slope half-slope method with a factor of 0.625 is applied to magnetic anomalies due to these models and depth is estimated for each model (Figure 2). Peters' rule gives the depth as 5/8 of the horizontal distance between the points on the side of an anomaly where the slope is half of the maximum slope (Sheriff 1980). Then, the estimated depths are compared with the actual depth values of the sources as in the models. The percentage errors for the various models are calculated. They show great discrepancies in certain profiles and with large variation for the same inclination at different depths of the source.

Plots of the percentage errors against inclination values are prepared (Figure 3). They show that the percent errors are minimum around inclination 45 degrees and they increased toward the equator and the pole. The problem arising in the plots is that the percent errors are ranging between positive and negative values, so for the same inclination angle, changing the factor will not solve the problem and at the same time does not reduce the errors for other inclination values. However, care should be taken when choosing the maximum slope and in turn the points at the tangent of the half slope. The estimated depth values are very sensitive to the measurement of the appropriate horizontal distances that will be multiplied by the factor which in fact depends upon the distance scale of the magnetic profile.

Many procedures have been tried by the authors to solve this problem, without success. One solution is found and presented by this study that can be followed to treat the estimated depths at various inclinations and it considered a procedure of depth correction. The adopted procedure uses the advantage of the relation between the depth of causative source and the maximum slope of the anomaly and the slight change in shape of the anomaly and amplitude at different depths. Plots between the actual and estimated depths against the horizontal distances between the tangential points of the half-slope line and the center of the maximum slope gives two straight lines intersecting at a certain point (Figure 4). These intersection points are characteristic of each inclination angle because they vary in position for the various inclinations or latitudes. It is easy to notice the gradual and regular changes in their positions as one moves from inclination zero to inclination 90°.

These plots can be used to adjust the estimated depth values for the specified inclination angle. A line projected from the point of intersection between the estimated depth value and the above mentioned horizontal distance (x) on Figure 2 on the plotted straight line of the actual depth will determine the difference in depth value that should be added to or subtracted from the estimated value. The difference for points above the intersection position of the two straight lines will be subtracted while those below are to be added. This procedure is then applied to known depths of thirty models (Figure l). It gives approximately 100% of the actual depth value after correction is applied to the estimated depth. In normal magnetic interpretation of field data the actual source depth of the causative magnetic body does not known unlike the models. This means that the intersection point obtained from the relation of the actual and estimated depths against the horizontal distance(x) will not be defined. Therefore as a rule of thumb, the vertical projection from the point of intersection of the estimated depth with horizontal distance will be either to the right or to the left of the straight line of the slope of the actual depth for the assigned inclination angle in Figure 4. Here, the slope line in Figure 4 of the actual depth for each inclination angle is considered as a standard relation that can be used to obtain the difference value. If the intersection point is to the right of the straight line of actual depth in the plot of Figure 4, the difference value should be added, while the difference should be subtracted if the point lies to the left of the straight line.

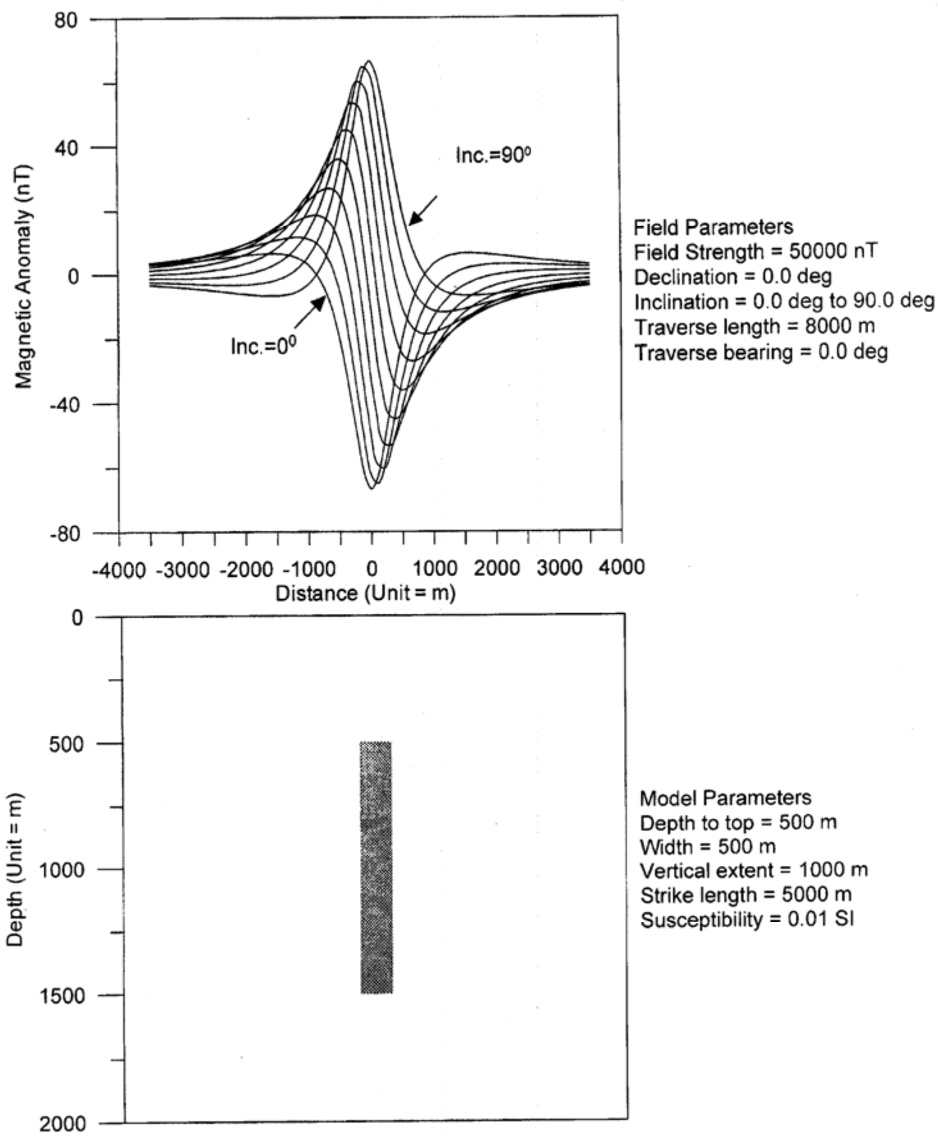

Figure 1. Total magnetic intensity profiles due to vertical thick dyke sources with the mentioned body parameters for inclination from 0° to 90°.

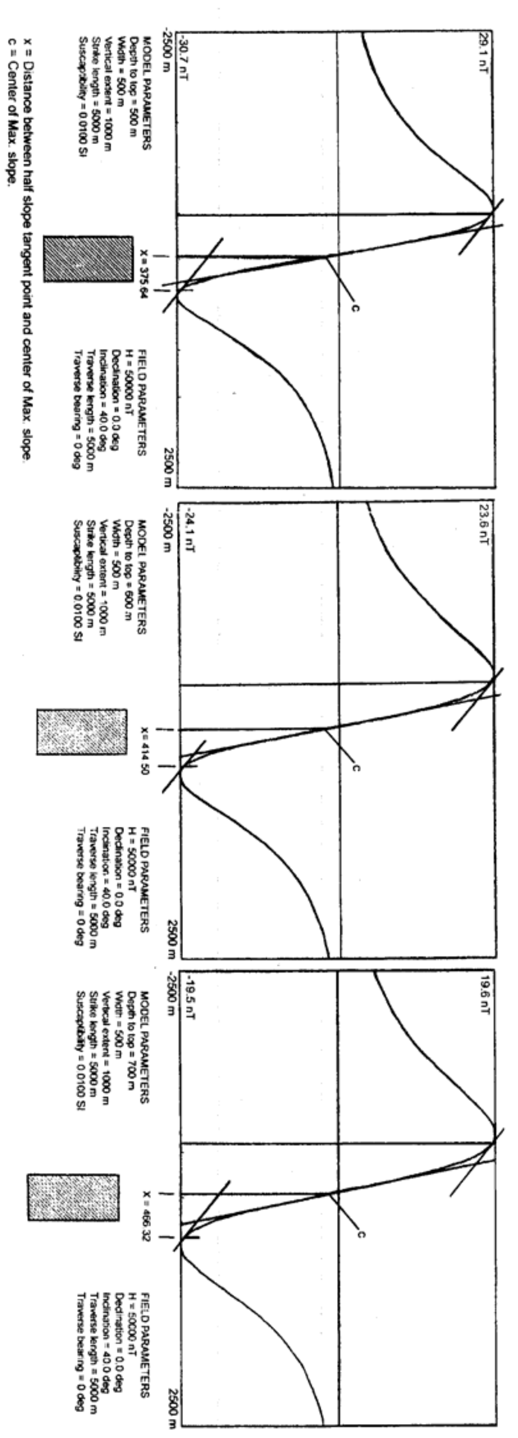

Figure 2. Procedure of depth estimation of magnetic source adopted in the present paper.

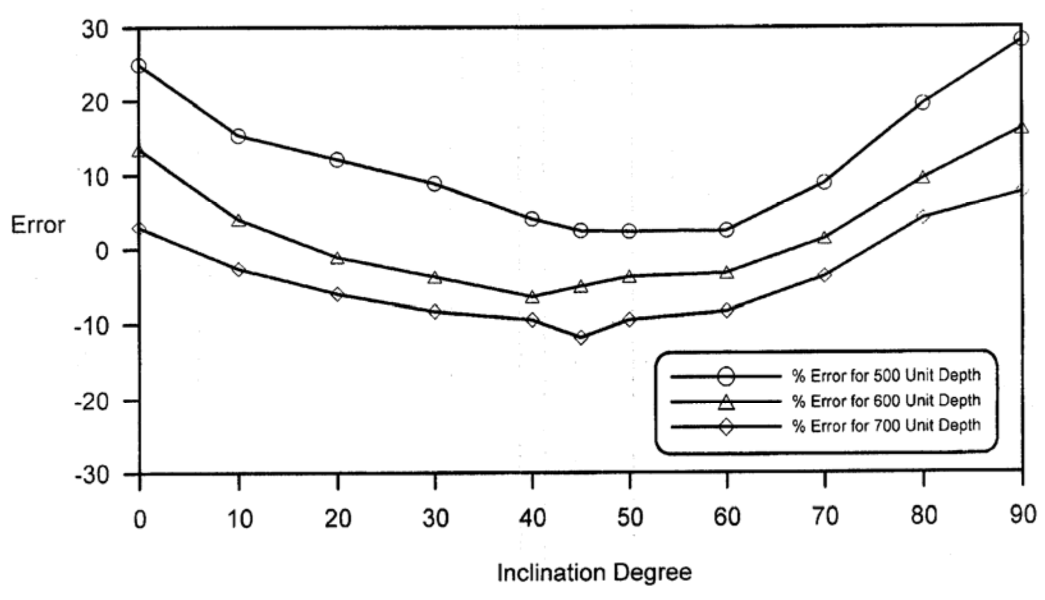

Figure 3. The variation of percentage errors for depth estimation against different inclination angles of the magnetic field calculated for dyke like models.

3. Application of the procedure

Application of Peters' method is accompanied by certain errors that may give serious discrepancies in the estimated depths of the magnetic anomalies. These results can be greater or smaller than the actual values by 30%, depending on the inclination values of the magnetic field and source depth (Figure 3). The proposed procedure of correction requires : a) applying the slope half-slope method carefully on the actual magnetic profile and then estimating the depth of the magnetic source, b) measuring the horizontal distance (x) between the tangential point of the half-slope and center of maximum slope as illustrated in Figure 2, c) converting the depth and distance values to an appropriate scale to fit the given scale of Figure 4 and d) defining the point of intersection of the estimated depth value with the horizontal distance on Figure 4 by using the assigned inclination angle. This point is used with the assigned inclination angle of the plot to project a vertical line on the straight line drawn for the actual depth to determine the difference value.

Figure 5 shows an example of the procedure followed in calculating the correction values for two cases having estimated depths of 512.8 and 580m and horizontal distances of 440.4 and 492.2m, respectively, for an inclination angle of 60°. The difference value of 12.8m is subtracted from the estimated depths of 512.8 while the value of 20 m is added to the estimated depth 580m. The final corrected depths are 500 and 600 which are the actual depths of the dyke models. These values are subtracted for the first case and added to the second case depending on the position of the intersection point which is to the left or the right of the line, respectively. The scale used in the plot here represents a unit distance and can be adjusted with the magnetic profile scale by multiplying or dividing the profile scale to fit with the plots of any given Figure.

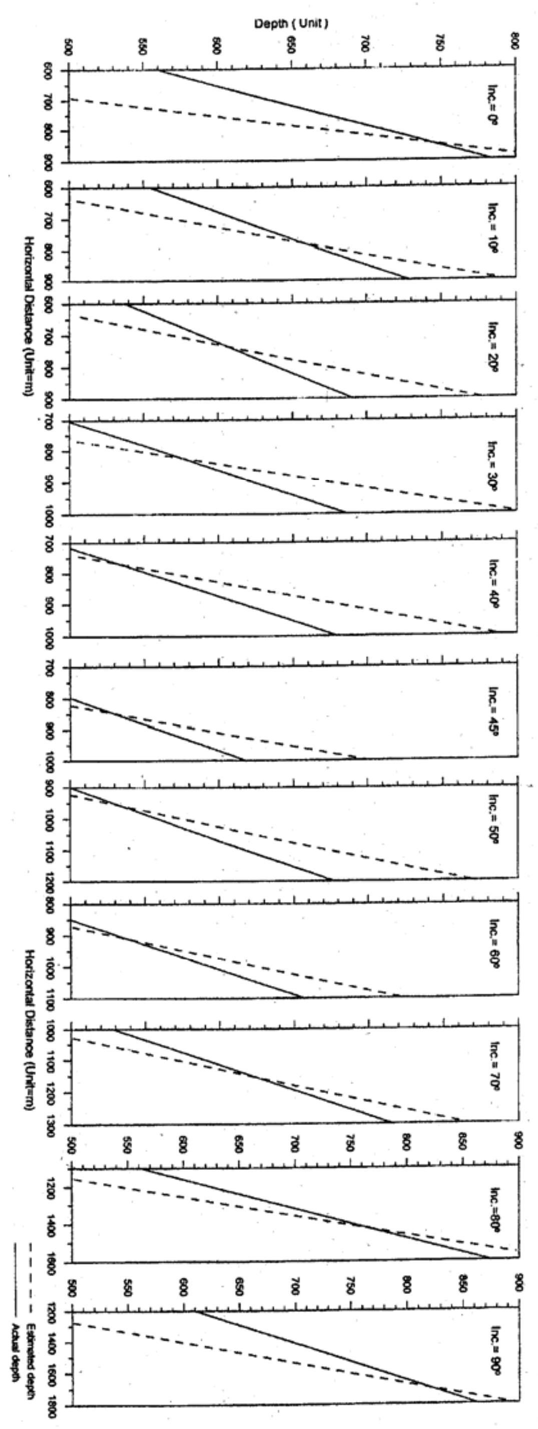

Figure 4. A plot the horizontal distance between the points of the half slope tangent and the central points of maximum slopes against actual depths of the model and the estimated depths by slope-half slope method.

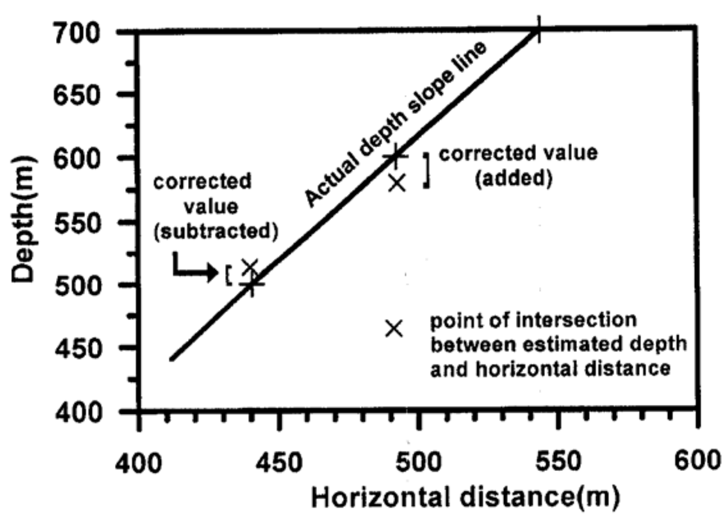

Figure 5. Illustration of the procedure followed to correct the estimated depth obtained by the present method. (actual slope-line for inclination 60°).

4. Field example

The published magnetic anomaly of the vertical component over the Pima copper mine in Arizona is considered here to check the above procedure of depth estimation. This anomaly had been analyzed by Gay (1963) and reinterpreted by Kara *et al.* (2003) through using displacement of the maximum and minimum by upward continuation. The adopted procedure in the present paper is applied to the total magnetic intensity of this anomaly (Figure 6). The slope half-slope method gives an estimated depth of 61.5 m for the source of this anomaly. Then this value is corrected by using the above nomographs of Figure 4. The corrected value is 4m which is subtracted from the estimated value and the final determined depth is 63.5m. An illustration of the procedure followed in determining the correct value is shown in Figure 1. The location of the intersect point between the estimated depth of 61.5m and horizontal distance of 13m is above (to the left) of the slope line for inclination 60°, so the value is subtracted. This value resembles nearly the depth value of the ore body which is 64m obtained by drilling (Gay 1963). This depth value is so near to the actual depth value and more acceptable than the values of 69.8m and 13m given by Gay (1963) and Kara *et al*. (2003) respectively.

5. Conclusions, discussion and recommendation

Depth estimated by slope half-slope method accompanied serious errors in model applications which should be considered in any calculation of magnetic source depths. Here, the profiles are too smooth and there are no difficulties in selecting the best lines for the maximum and half-slopes and therefore, care should be given to field data. Any slight change in the measured distances will create great effects in the calculated depth values and in turn produce wrong results and these depend upon the used distance scale. Therefore, one should consider the subjective errors to avoid such mistakes. With these cautions, the method still has big errors in low and high latitudes and required correction to those estimated depths. The question is whether the estimated value is larger or smaller than the actual depth. The answer is too difficult because no one knows the actual depth of the magnetic source. The proposed procedure given in the present paper provides an easy solution to this problem and can define the positive or negative difference values and at the same time it will be very useful in magnetic interpretations.

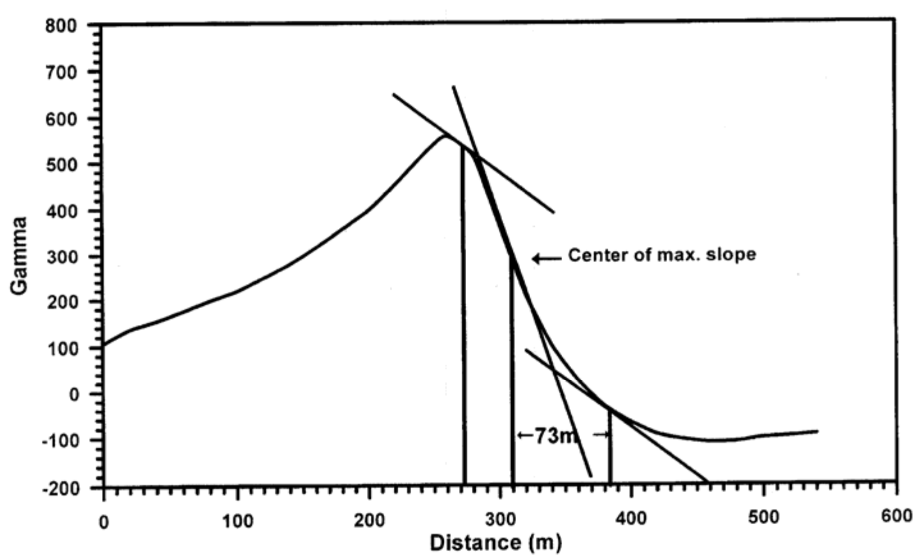

Figure 6. Total magnetic anomaly taken from Kara *et al.* (2003) used as an example in depth estimation by applying the present procedure. (estimated depth = 67.5 m).

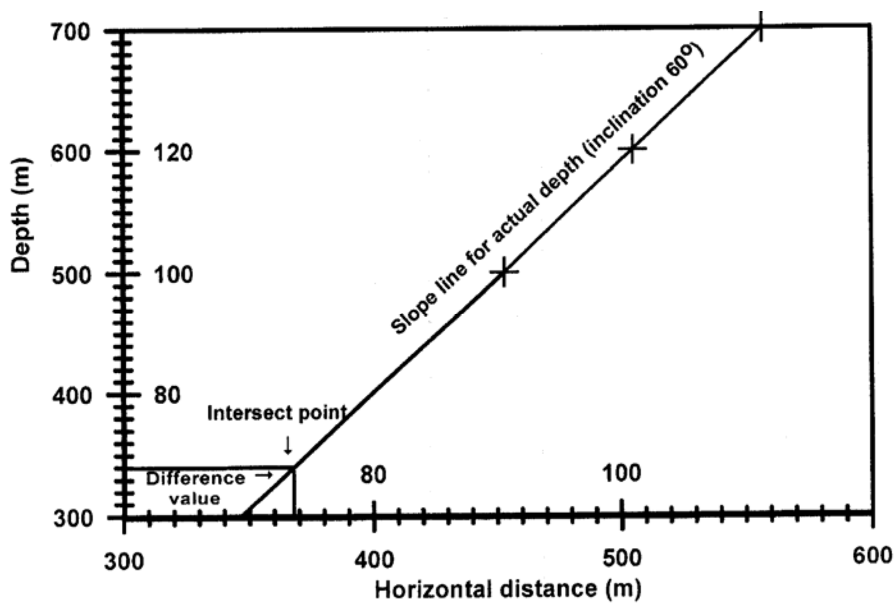

Figure 7. Illustration of the procedure used to calculate the difference between the estimated value and the actual value from the intersection point between the estimated depth and the horizontal distance for the field example.

Although the present procedure uses certain plots and mostly works with recent days done by computer, it can be translated in future to certain equations that make application so simple. Understanding the procedure is one of the tasks and the steps of calculation can be followed by the illustrations given in Figures 5 and 7. The present procedure can be recommended since depth estimation for magnetic sources is still a problem. The correct depth will assist the interpreter to obtain a constraint parameter that will give a good model fitting because magnetic interpretation includes many variables, which complicate the final results. Determination of the correct depth is very useful as a forward step in magnetic interpretation.

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