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# DETECTION OF INCLINATION AND DECLINATION ANGLES FROM TOTAL MAGNETIC ANOMALY MAPS ON ARCHAEOLOGICAL SITES

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**Abstract.** We considered determining the inclination and declination angles from the total magnetic anomaly maps on archaeological sites. It is necessary to know the magnetic inclination and declination angles of the study area in order to accurately locate the buried structures on the total magnetic anomaly maps. To this end, we used the Dannemiller and Li method. We calculated inclination and declination angles for both synthetic model and archeological total magnetic field data.

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# 1 Introduction

For determining and interpreting the properties of magnetic data sets or anomalies properly, it is crucial that the total magnetization direction is accurately determined. Magnetization should not be considered as induced magnetization only. The total magnetization of the effective source is the vector sum of induced and remanent magnetization [1]. The presence of remanent magnetization can change the magnetization direction. For this reason, inaccurate results can be obtained about the size and shape of the effective sources that cause the anomaly during the interpretation phase.

In this context, many studies have been carried out. Zietz and Anderson [2] examined the relationship between position and intensity of the maximum and minimum obtained by a model body. Roest and Pilkington [3] made the correlation between the amplitude of the total gradient of the magnetic field and the horizontal gradient of the pseudogravity. In order to calculate the magnetization direction from the reduced-to-pole (RTP) field computed at different directions of the magnetization vectors, Fedi et al. [4] proposed the MAX-MIN method. Bilim and Ates [5] evaluated the total magnetization direction by determining the maximum correlation between pseudogravity and gravity anomalies. Phillips [6] developed a method using Helbig's [7] integral relationships to estimate the vector components of the magnetic dipole moment from the first-order moments of the vector magnetic field components. The magnetization direction of crustal structures has been computed by Nicolosi et al. [8] by using an equivalent source algorithm. Gerovska et al. [9] obtained the magnetization direction of magnetic anomalies by correlating the RTP field with the size transformation. Li et al. [10] made the estimation of the magnetization direction of magnetic anomalies through correlation of the RTP field with the normalized source strength (NSS) anomalies.

As with geomagnetic studies for various purposes, obtaining the highest and most efficient results from magnetic maps in archaeological areas is essential. During the planning of archaeological studies, the location and depth values of the potential buried structures in the survey area can be estimated with the help of total magnetic anomaly maps. Therefore, at the stage of detecting the structures on magnetic maps, adverse effects should be eliminated. Suppose the magnetic inclination angle is different from actual value. In that case the RTP (Reduction to Pole) process can be performed incorrectly, and the location values of potential structures can be determined in different regions than they should be. In this study, the inclination and declination angles were calculated for both synthetic model and field data by using the approach introduced by Dannemiller and Li used in determining the direction of magnetization.

# 2 Dannemiller and Li Method

The basis of the Dannemiller and Li method is the correlation of the vertical and total gradient of the Pole reduced field, which is frequently used in the interpretation of magnetic data. Both values are attenuated at the same rates depending on the source depth. The total field data obtained from reduction to pole is produced as if the inclination angle was measured in the vertical direction, but the magnitude remained the same. The total magnetization direction ($\hat{M}_t$) must be known in order to perform this process correctly. When an incorrect direction is used, the operations will continue numerically. However, the resulting anomaly value $R(\hat{M})$ reduced to the pole will be more asymmetrical than the correctly reduced anomaly [1] .

The correlations of the total and vertical gradients of the anomaly reduced to the pole are symmetrical when they are maximized and calculated using the correct magnetization direction. Although there is no analytical evidence of this situation, it is seen on 2D samples in Figure 1 that it is successful when it is experimentally applied to the observation values in practice. The correlation of the vertical gradient with the total gradient of the field reduced to the pole on the vertical dyke, and the dipping dyke is exemplified. The inclination of both dykes is $60^o$. As a result (in solid lines), it is seen that it reaches approximately the highest correlation value at the correct inclination value for both dykes. The dashed lines show the correlation between the horizontal gradient and the total gradient of pseudo-gravity. However, while this method gives accurate results for vertical dykes, it shows changes if the effective source is in dipping form.

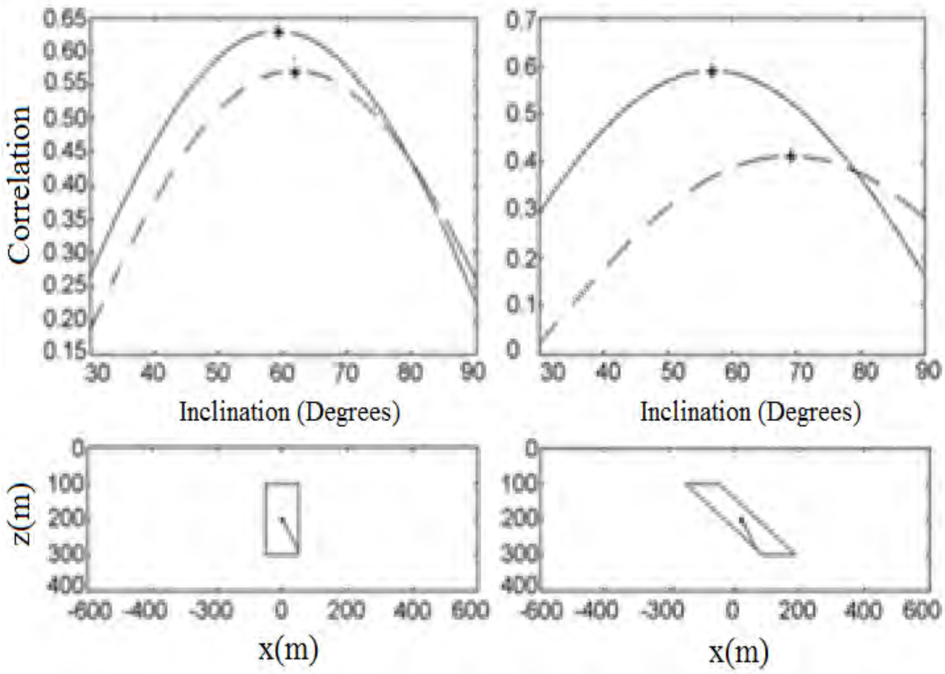


Figure 1: Cross correlation coefficients between the vertical gradient and the total gradient of the area reduced to the pole according to different inclination angles [3].

This method assumes total field anomalies as data. As a first step in the estimation process, a half reduction to pole was performed using the known direction of the inducing field. In this way, the data is transformed into vertical anomalies, and only the effect of the magnetization direction is considered. In order to perform half reduction to pole (HRTP), Dannemiller and Li [1] transformed the data to the Fourier domain and applied a multiplication operator,

$$\psi_{HRTP} = \frac{\sqrt{\omega_x^2 + \omega_y^2}}{\left(\vec{K} \cdot \hat{B}_0\right)} \tag{2.1}$$

Where $\omega_x$ and $\omega_y$ are the wavenumbers in the x and y directions, $\hat{B}_0$ is the unit vector of induced field and $\vec{K} = (i\omega_x, i\omega_y, \sqrt{\omega_x^2 + \omega_y^2})$.

When the continuation with vertical derivative anomalies and estimation has continued, a set of numerical values obtained by applying another half RTP operator with a trial magnetization direction is used. The second HRTP process (R) by replacing the directional vector $\hat{M}$ with the operator in Equation 2.1 can be expressed as;

$$v\left(I_M, D_M\right) = \frac{\partial R}{\partial z}, \tag{2.2}$$

$$t(I_M, D_M) = \sqrt{\left(\frac{\partial R}{\partial x}\right)^2 + \left(\frac{\partial R}{\partial y}\right)^2 + \left(\frac{\partial R}{\partial z}\right)^2} \tag{2.3}$$

where the vertical derivative and the total gradient are represented v and t, respectively. Since the vertical and total gradients are calculated, the cross-correlation coefficients can also be evaluated according to the following equation;

$$C(I_M, D_M) = \frac{\sum\left(v_j - \bar{v}\right)\left(t_j - \bar{t}\right)}{\sqrt{\sum\left(v_j - \bar{v}\right)^2 \sum\left(t_j - \bar{t}\right)^2}} \tag{2.4}$$

Here, the index of each value in the data set j, and $\bar{v}$ and $\bar{t}$ are the means of the vertical derivative (v) and the total gradient (t), respectively.

## 2.1 Synthetic Model Application

In order to interpret the field data, inclination and declination angles of the study area are required at the data improvement stage (reduction to the pole). An application of this process is tested on a synthetic model using the Dannemiller and Li method. The model has five prismatic blocks with varying magnetic susceptibility values, size, and depths (Table 1). Initial values of magnetic field strength, inclination, and declination angles are 45000 nT, $65^o$, and $45^o$. Figure 2a and Figure 2b show the 3D spatial location and the 2D top view of the model. The noise-free magnetic anomaly map computed by our synthetic model is shown in Figure 3.

Dannemiller and Li method was applied to the total magnetic anomaly map of the synthetic model shown in Figure 3. The contour plots of the correlation coefficients are shown in Figure 4. The regions with the highest correlation values show the values closest to the true values of the inclination and declination angles. In Figure 4, the correlation coefficients peak at an inclination of $65^o$ and the declination of $45^o$. These values are consistent with the initial values entered into the model.

Table 1: Synthetic model parameters.

| **Block No** | **Y Axis** | | **X Axis** | | **Depth Values** | | **Magnetic** |
|---|---|---|---|---|---|---|---|
| | **Y1(m)** | **Y2(m)** | **X1(m)** | **X2(m)** | **H1(m)** | **H2(m)** | **Susceptibility (SI)** |
| 1 | 2 | 13 | 2 | 3 | 0.5 | 3.5 | 0.020 |
| 2 | 12 | 13 | 3 | 9 | 0.5 | 3.5 | 0.020 |
| 3 | 7 | 9 | 4 | 9 | 1.0 | 2.0 | 0.010 |
| 4 | 5 | 6 | 4 | 8 | 0.5 | 1.0 | 0.015 |
| 5 | 1 | 4 | 5 | 9 | 1.0 | 2.5 | 0.012 |

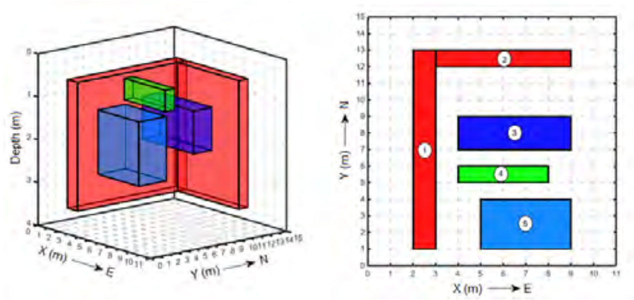


Figure 2: Synthetic Model a) 3D Geometric location, b) 2D view of the model.

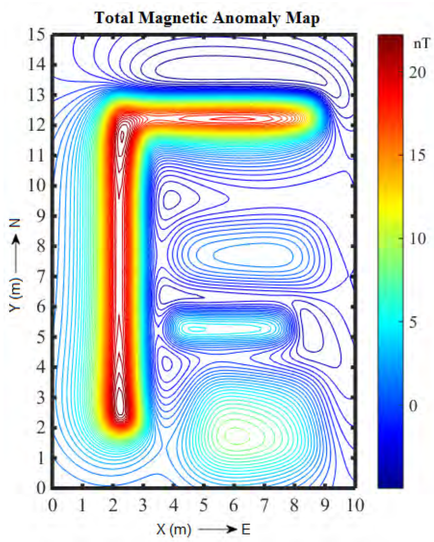


Figure 3: Total magnetic anomaly map of the synthetic model (inclination angle $65^o$, declination angle $45^o$).

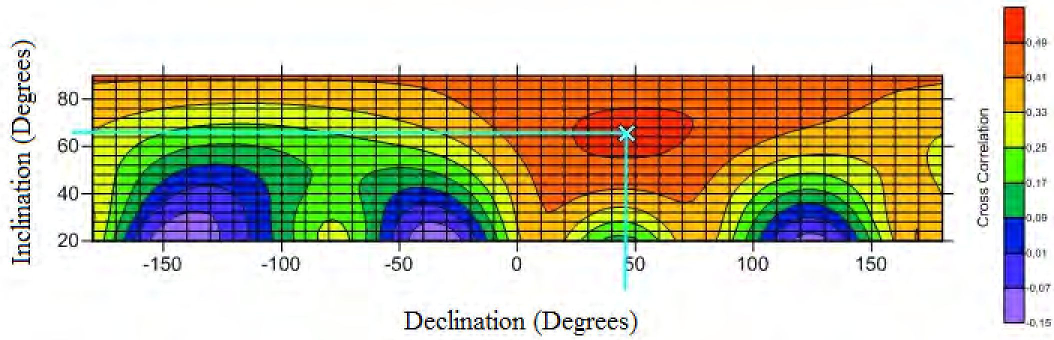


Figure 4: Inclination and declination angles are calculated from Dannemiler and Li method.

## 2.2 Field Application

In this section, Dannemiller and Li method is applied to real data. Magnetic data are collected on the Amasya - Oluz Mound archeological field. The field is located between 34 ° 57 '06" - 36 ° 31 '53" East Longitude and 41 ° 04 '54" - 40 ° 16 '16" North Latitude on the Central Black Sea part of the Black Sea Region (Figure 5). The dimensions of the mound are 280 x 260 m., and it has an almost circular shape with a size of approximately 130-140 m. (Figure 6). Excavations and geophysical studies have been carried out systematically in the region since 2007.

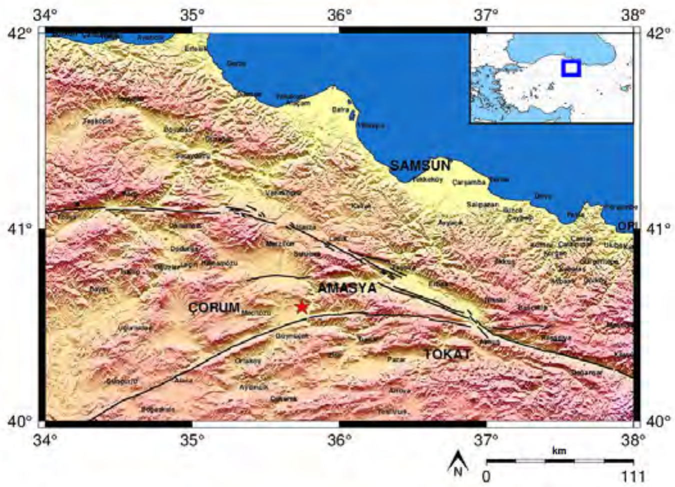


Figure 5: Amasya Oluz Mound location Map.

The magnetic data of the study area were collected with Littlemore typ 820 Proton Magnetometer. The survey grid of the field has a length and width of 30 × 40 meters and profile intervals of 0.5 x 0.5 meters. Total magnetic anomaly map was calculated. By applying upward continuation to the total magnetic field data, the disturbances caused by the noise were removed from the data. Figure 7 shows the Upward continuation map of the Amasya Oluz Mound archaeological field.

Figure 6: Drone view of Amasya Oluz Mound

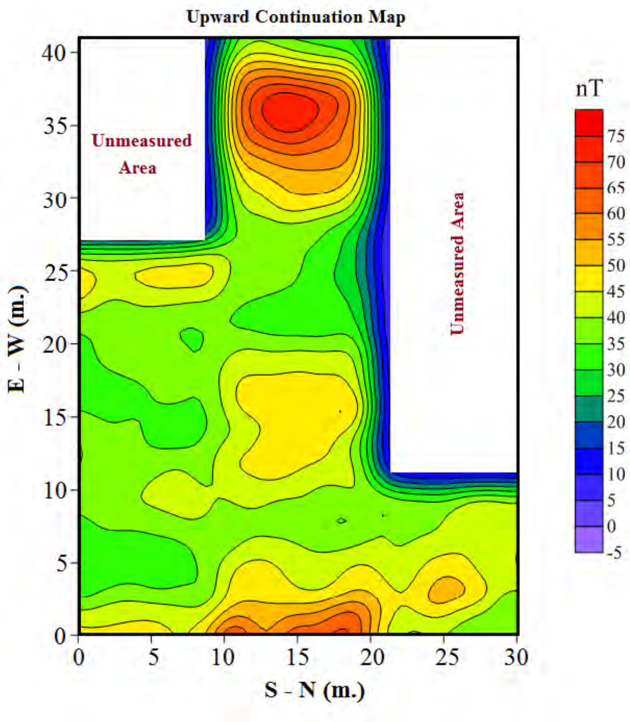


Figure 7: Upward Continuation map of Amasya Oluz Mound archaeological field.

The most critical parameters affecting the anomaly shape in the anomalies obtained from magnetic data are the inclination and declination angles of the region. In order to determine the effective source boundaries accurately, the effect of the inclination angle must be removed from the data by applying the reduction to pole and using symmetrical anomalies.

For this purpose, the contour plot created from the correlation values obtained by using the filtered map given in Figure 7 using the program prepared in MatLab environment for Dannemiller and Li method is shown in Figure 8.

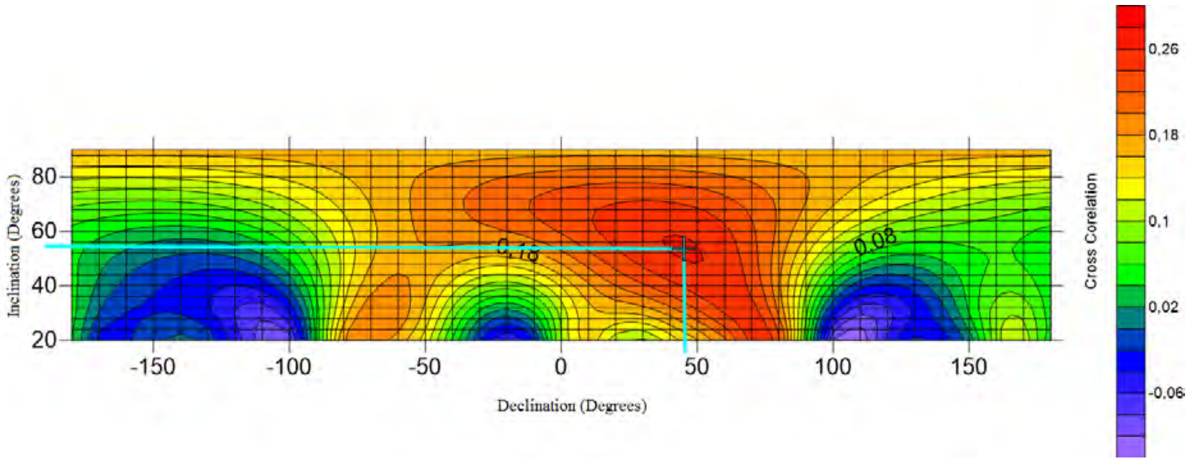


Figure 8: The correlation coefficients from Dannemiler and Li method. The inclination and declination angles are $54^o$ and $45^o$, respectively.

Considering the region where the correlation coefficients are maximum, it has been determined that the inclination angle of the study area is $54^o$, and the declination angle is $45^o$.

## 3 Conclusions

Knowledge about the magnetic inclination and declination angles has a significant role in magnetic interpretation. In case of lack or inaccuracy of this information, determinations of the subsurface sources are erroneous. The actual inclination and declination angles of the area must be known for the pole reduction process to give correct results. This situation will cause the subsurface archaeological complexes to be located in different places and distribution than their potential locations due to an incorrect evaluation. We applied the Dannemiller and Li method for both synthetic and archaeological total magnetic field data in this context. For the synthetic model, the results of inclination and declination angles are determined as $65^o$ and $45^o$, respectively. These values are consistent with the initial values entered into the model. For the total magnetic anomaly map (Upward continuation) of Amasya Oluz Mound archeological site, inclination and declination angles are determined as $54^o$ and $45^o$, respectively. The accurate results of the method show its usability in archaeogeophysical studies. In this way, the locations of potential building edges can be determined consistently over the total magnetic anomaly maps used in the planning of archaeological surveys.

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