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Modeling of the Ancient City of Kerkenes (Yozgat-Turkey) Magnetic Anoma MAP

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Abstract Geophysical methods are used to display and model buried archaeological artifacts. Studies using magnetic method in archaeological sites provide fast and effective solutions. Generally, magnetic method is used to extract city plans and find buried roads and structures. In particular, residual magnetizations resulting from furnaces or fires create strong magnetic anomalies. Since 1993, geophysical studies have been carried out at the Kerkenes Mountain archaeological site. In the study, the magnetic anomaly of the dyke-type structure in this area was interpreted with nomograms, with a section taken from the magnetic anomaly map taken from the data obtained from these measurements.

Keywords Kerkenes ancient city, magnetic, nomogram method, archeogeophysics

Introduction

In magnetic studies, it is possible to model anomalies caused by geological structures of any shape. Due to the irregular shapes of geological structures, it is not possible to identify such structures analytically. In most of the known methods, the geological structure was determined with a mathematical model suitable for its shape and calculations were made on these models. Geological structures that give magnetic anomalies are usually compared to simple geometric shapes because the calculations are long and complex, and mathematical models are built according to these figures. The interpretation of magnetic maps is usually done to determine the depth, dip, width and susceptibility of the source. Calculating such structures is a very tiring and long task, although it is wrong in practice. However, interpretations are successful if the source is simple geometric figures. Recently, the wavelet transform has been used in the evaluation of archaeological data. They presented a modeling approach using Wavelet theory for archaeological potential anomalies [1]. They evaluated archaeological sites using wavelet transforms and detected buried structures using the improved horizontal derivative [2]. He revealed archaeological structures in the remains of the Hittite civilization in Turkey by using image processing method [3,4]. She modeled the structures by using various filters on magnetic data by doing archaeological geophysical study in Kerkenes (Yozgat) field [5]. They used various techniques to find magnetic anomalies of three-dimensional dyke and fault-type structures of any shape. and they went to the method of calculating fault parameters. They interpreted magnetic anomalies using characteristic curves or points in these methods [6,7].

Method

An XOY coordinate system is used to formulate the magnetic anomalies of the dyke and vertical fault models. In this coordinate system, the Y axis is the direction of extension of the object, and the magnetic profile is perpendicular to this axis and in the direction of the X axis, which makes an α angle with the magnetic level. Io is the inclination of the strong magnetic field T, Jo is the inclination of the resultant magnetization, and a is the equivalence angle. Io' is defined as the effective inclination angle in the induced magnetization state, and Jo' is defined as the effective inclination angle of the resultant magnetization at which induced and residual magnetization occurs [8].

Io'= arctan(tanIo/cos α)   Jo'=arctan(tanJo/cos α)

Dyke Model

On a profile taken perpendicular to the elongation of the dyke with an inclination angle δ, which is exposed to a linear regional value with a base level of C and a slope of M, extending to an infinite depth, the geometric position of which is shown in Figure 1, it will form a general measurement point S at a distance X from the arbitrary origin point R. The magnetic anomaly value is calculated with the following equation [9].

$$F(X) = P\left[0.5\sin Q \ln\frac{(X-D+B)^2+H^2}{(X-D-B)^2+H^2} + \cos Q\left\{\tan^{-1}\frac{X-D+B}{H} - \tan^{-1}\frac{X-D-B}{H}\right\}\right] + MX + C \quad (1)$$

Here, P is the amplitude coefficient and Q index parameter, and the equivalents of the 3 components of the magnetic anomaly (vertical, horizontal and total) are given in Table 1. H and B represent the upper surface depth and half width of the dyke, respectively. D is the distance from the arbitrary point of origin to the center of the dyke [9].

Table 1: Equivalents of amplitude coefficient P and index parameter Q [9].

Anomaly	P (amplitude coefficient)	Q (index parameter)
• horizontal component	$2KT\beta(1-\cos^2 I_0 \sin^2\alpha)^{1/2}(1-\cos^2 I_0\sin^2 a)^{1/2}$	$I' + J' - \delta - 90$
• vertical component	$2KT\beta(1-\cos^2 J_0\sin^2 a)^{1/2}$	$J' - \delta$
• total component	$2KT\beta\cos\alpha(1-\cos^2 J_0\sin^2 a)^{1/2}$	$J' - \delta - 90$
• $\beta = \sin\delta$		
• inducend magnetism	$J_0 = I_0$, $a = \alpha$ ve $J' = I'$.	

This, X=x/h ve R=2b/h dir.

max./min. in F(x). condition (1) from equality,

$X^2+2X.CotQ-(1+R^2/4)=0$ (2)

becomes the roots of equation (2) corresponding to the maximum (XM) and minimum (Xm) points of F(x)

$XM=-CotQ+(cosec^2Q+R^2/4)^2$ (3)

$Xm=-CotQ-(Cosec^2Q+R^2/4)^2$ (4)

available as.

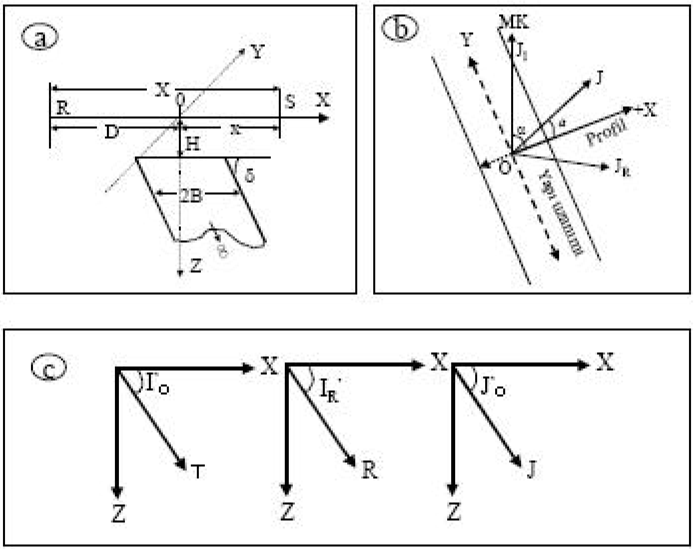

Figure 1: a) Dyke geometry, b) Plan view of the magnetized dyke, c) The appearance of magnetization vectors in the XZ plane [7]

D=/(XM-Xm)/(XM+Xm)/ (5)

If it is defined as the equation (3) and (4),

$D=/(2.\cos Q)/(4+R^2.\sin^2.q)^{1/2}/$ (6)

obtained. It is clearly seen that the ratio D depends only on R and Q. Let's define the other A as follows.

A=/(FM-Fm)/(FM+Fm)/ (7)

$FM=P[\sin Q.Ln[((XM+R/2)^2+1))/((XM-R/2)^2+1)]^{1/2} + \cos Q[\arctan(XM+R/2)-arcan(XM-R/2]]$ (8)

$Fm=P[\sin Q.Ln[((Xm+R/2)^2+1))/((Xm-R/2)^2+1)]^{1/2} + \cos Q[\arctan(Xm+R/2)-arcan(Xm-R/2]]$ (9)

It is possible

XM and Xm were defined as (3) and (4). If placed in the equations

A=a1/a2 (10)

obtained.

a1 and a2 are as follows.

a1=2cosQ.arctan(R/2) (11)

$$a2=0{,}5.\sin Q.Ln\left[\frac{2+R^2.\sin^2Q+R.\sin Q.(4+R^2.\sin^2Q)1/2}{2+R^2.\sin^2Q-R.\sin Q.(4+R\ .\sin^2Q)^{1/2}}\right]+ \quad (12)$$

$$\cos Q.\arctan\left[\frac{2+R^2.\sin^2Q+R.\sin Q.(4+R^2.\sin^2Q)1/2}{2+R^2.\sin^2Q-R.\sin Q.(4+R^2.\sin^2Q)^{1/2}}\right]$$

As can be seen from the equations, the ratio A depends on the R and Q values of the dyke. Thus, the ratios A to D are affected only by R and Q.

In marking A versus D for various combinations of R and Q, the pair of D and A values corresponds to a single set of R and Q values. This rule was also used in the preparation of nomograms.

limits for D and A;

In equation (6), when Q=0° is taken, D=1 and when Q=90° is taken, D=0. So the limits for Q are, $0\leq D\leq 1$ and similarly, when the same operations are done for A, $0\leq A\leq 1$ is found.

Vertical fault model

Similar to the dyke model, magnetic anomalies in the three components along a profile perpendicular to the extension of a vertical fault belong to a single group. Horizontal component equation (Figure 2);

$$H=2ktZo\{[(z-x\cot I \sin\beta)/r1^2]-[(z-(x-b)\cot I \sin\beta)/r3^2]\} \quad (13)$$

Thus, the total area;

$$F=2ktFo\{[2z \cos I \sin I \sin\beta + x(\sin^2 I- \cos^2 I \sin^2\beta)]/r1^2 - [2z \cos I \sin I \sin\beta+ (x-b)(\sin^2 I- \cos^2 I \sin^2\beta)]/r3^2]\} \quad (14)$$

Above, z is the depth of the fault and t is the thickness of the fault. If the fault has a finite length, the total area is;

$$F=2ktFo\{[x-b(\cos^2 I \sin^2 I \sin^2\beta) - 2z \sin I \cos I \sin\beta]/r2^2\sqrt{(1+r2^2)}/Y^2 -[x(\cos^2 I \sin^2 I \sin^2\beta) -2z \sin I \cos I \sin\beta]/ r1^2\sqrt{(1+r1^2)}/Y^2\} \quad (15)$$

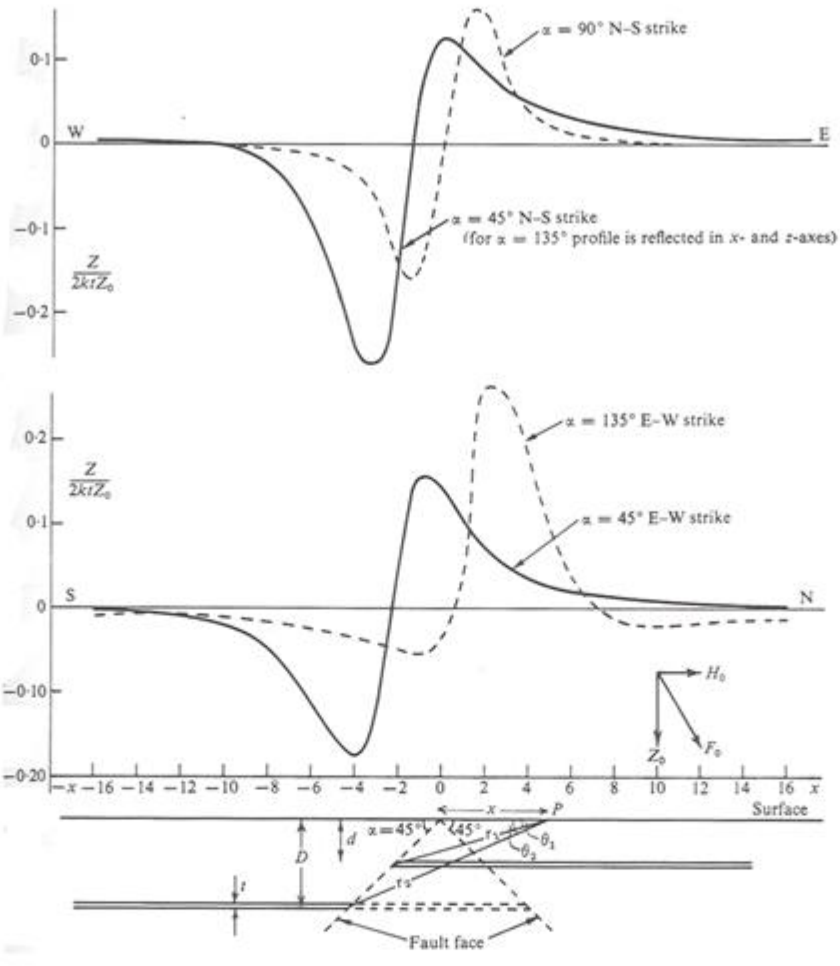

Figure 2: Approximate fault slip for the thin layer, Z profile [9]

Semi-infinite vertical fault models are used in order to obtain efficient results in fault predictions, as well as in gravity studies, in magnetic studies. In a vertical semi-infinite fault model with $r3=r4=\infty$ and $\varphi1=\varphi3=t$ The relationship between them is as follows [9].

$$Z = 2k \sin\alpha\{(H_0 \sin\beta \sin\alpha + Z_0 \cos\alpha) \log (r_2/r_1) + (H_0 \sin\beta \cos\alpha - Z_0 \sin\alpha)(\phi_1 - \phi_2)\} \quad (16)$$

$$Z' = 2k \sin \alpha \left\{ (H_0 \sin \beta \sin \alpha + Z_0 \cos \alpha) \log \left(\frac{r_7}{r_8} \right) + \right. \\ \left. + (H_0 \sin \beta \cos \alpha - Z_0 \sin \alpha)(\phi_8 - \phi_7) \right\}, \tag{17}$$

$$Z'' = 2k \sin\alpha \left\{ (H_0 \sin \beta \sin \alpha + Z_0 \cos \alpha) \log \left(\frac{r_2 r_7}{r_1 r_8} \right) + \right. \\ \left. + (H_0 \sin \beta \cos \alpha - Z_0 \sin \alpha)(\phi_1 - \phi_2 - \phi_7 + \phi_8) \right\}. \tag{18}$$

The east west (EW) and north-south (DB) offsets along the two profiles are shown in the figure 3.

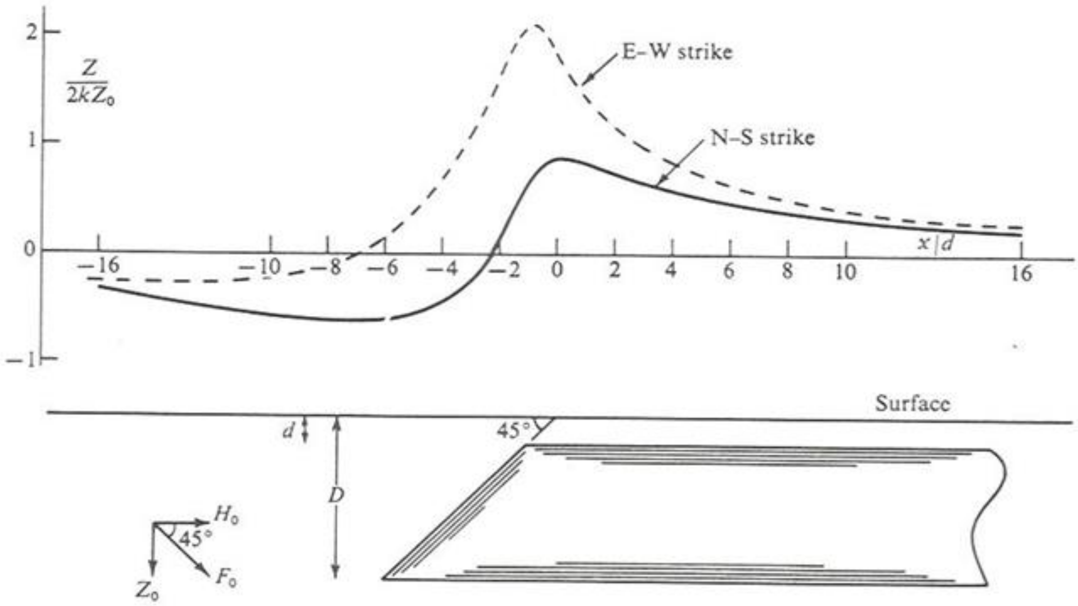

Figure 3: Semi-infinite fault model [9]

Preparation of Nomograms

It is prepared depending on the changes in A and D values for different values of R and Q. While the curves in the nomograms are prepared for R=0,1,2,3,4,5,6,8,10,15 and 20, the index parameter Q varies between 0° and 90°. F(x) curves other than these are mirror symmetric of the curves between these angles. Since R=0 in the case of a very thin dyke, it can easily be seen that for any value of Q D=A D is equal to A and the slope is equal to one [6].

Comparison of Nomograms for Dike and Vertical Fault

The A and D ratios used in the interpretation of the nomograms prepared for the dyke and vertical fault in magnetic studies are found by using the equations (6) and (7). Previously, the maximum and minimum values and their distances from the origin are determined from the anomaly curve.

The anomaly curve of F(x), where A>D belongs to a dyke family, A<D to a fault family, and A=D to a thin plate family.

Qualitative comparison between nomograms of dyke and vertical fault models can be made from figures (4) and (5).

Dyke model nomograms are characterized by ratios A and D where A is always greater than D for R > 0. In case of A=D representing thin plate, R=0. [6].

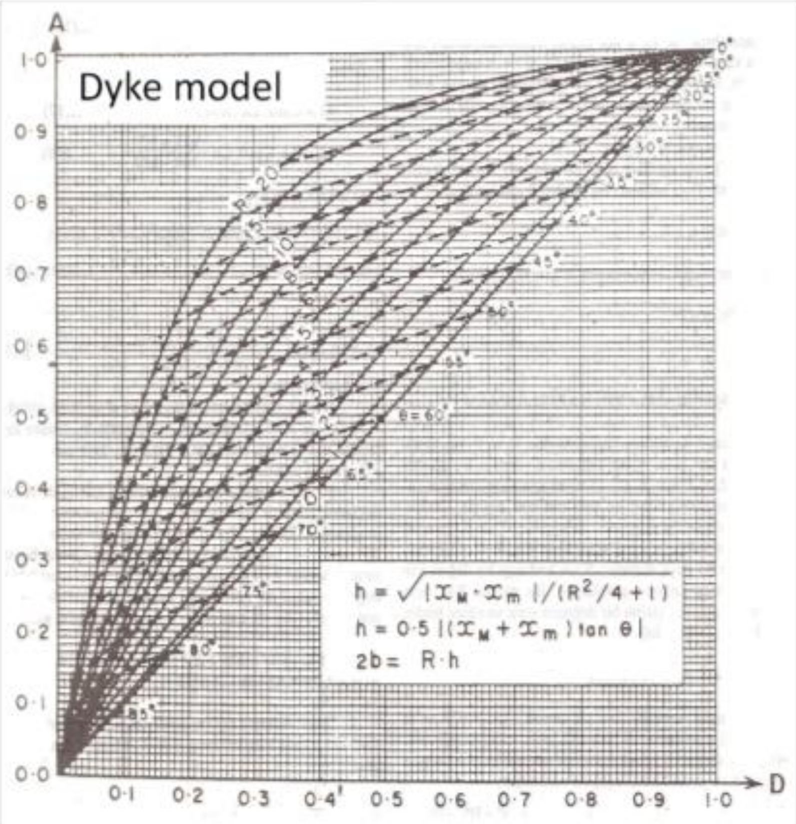

Figure 4: The nomogram for the dyke model [7]

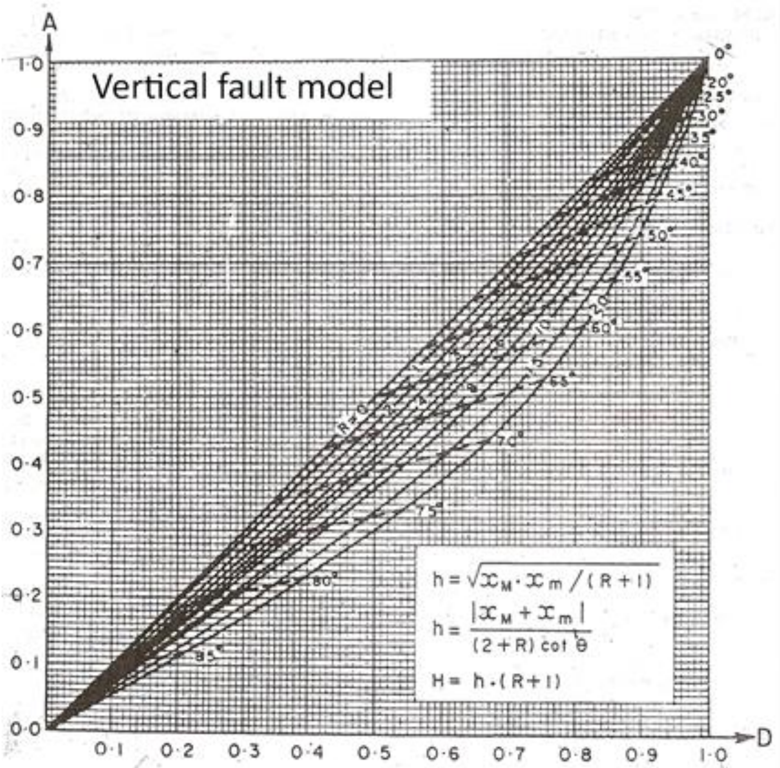

Figure 5: The nomogram for the vertical fault model [7]

Vertical fault nomograms are characterized by ratios A and D, where A is always less than D for R=0. Thus, the A and D ratios can be used to interpret the structure formed by a dyke, plate, or vertical fault.

Magnetic Parameters

It is often difficult to establish a data level for assessment in magnetically studied fields. It is not very possible to match the data obtained from simple shapes with real terrain data (Figure 6). However, in order to eliminate these problems, relations that give the depth, width and dip angle of the dyke or fault extending to infinity have been developed [9]

$$Z=2k \sin\alpha\{(Ho \sin\beta \sin\alpha + Zo \cos\alpha) \log(r3/r1) + (Ho \sin\beta \cos\alpha - Zo \sin\alpha)(\varphi1-\varphi3)\} \quad (19)$$

$$r1^2=d^2+(x+b)^2,\ r3^2=d^2+(x-b)^2 \quad (20)$$

$$\varphi1=1/\cot(x+b)/d,\ \varphi3=1/\cot(x-b)/d \quad (21)$$

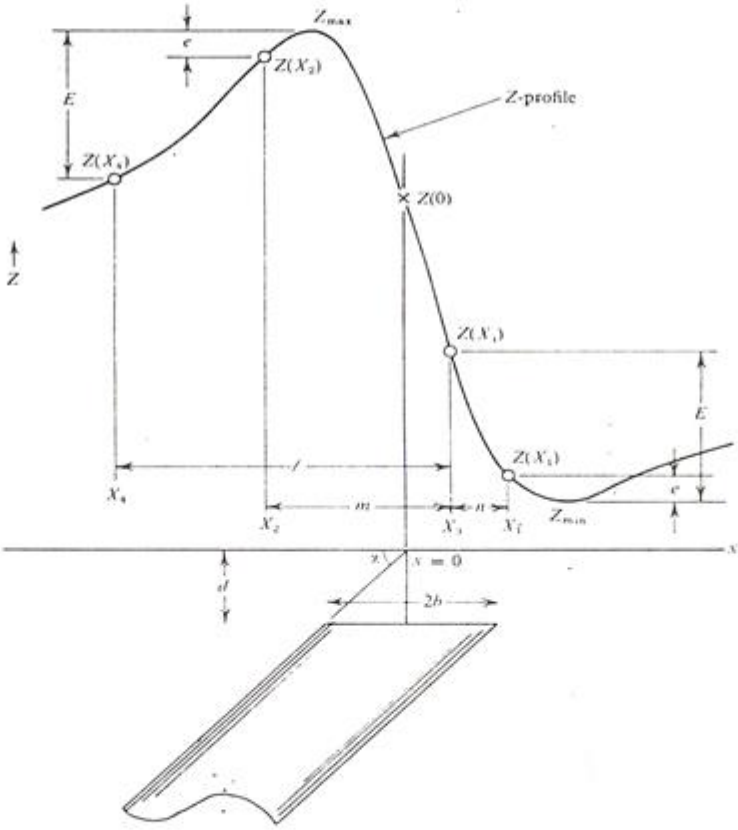

Figure 6: Endless dyke model [9].

Dimensionless parameters were tried to be obtained by division by d.

X=x/d ve B=b/d,

$$Z=M\{1/\cot(X+B)-1/\cot(X-B)+(N/2)[\log\{(X-B)^2+1\}\log\{(X+B)^2+1\}] \quad (22)$$

In this equation, the first term is known as the symmetric component of the profile, and the second term is known as the antisymmetric component of the profile (Figure 7).

At X=0, the conjugate points X1 and X2 are selected on the dyke profile so that the Z value is equal to the total value.

$$Z(X1)+Z(X2)=Z(0) \quad (23)$$

corresponding to symmetric and antisymmetric components.

$$S(X1)+S(X2)=S(0),\ A(X1)+A(X2)=0 \text{ dır.} \quad (24)$$

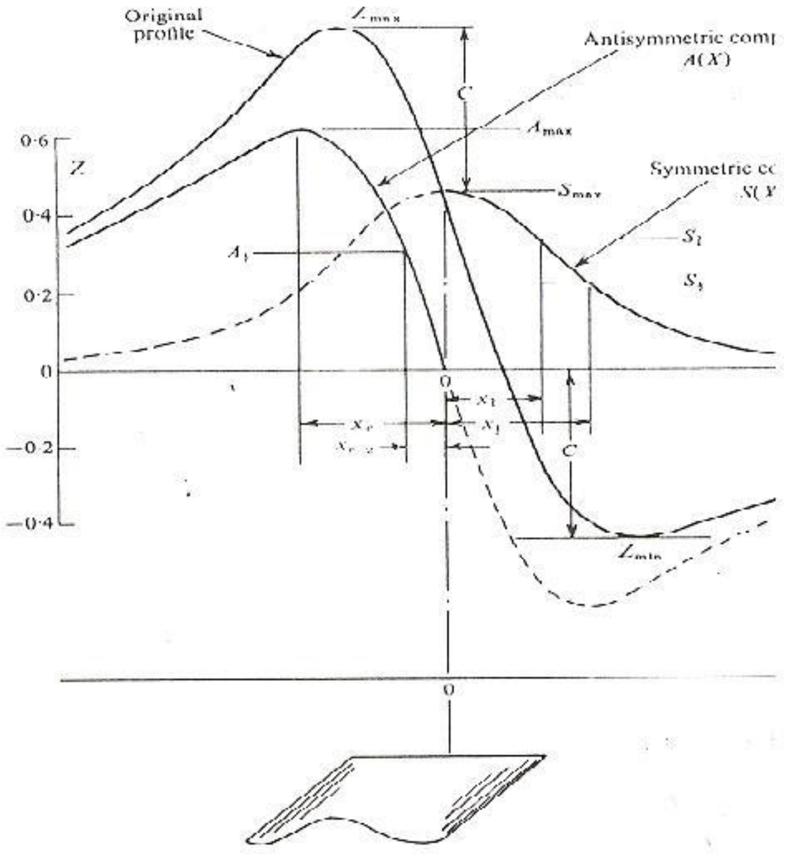

Figure 7: Finding the zero line on the anomaly [9]

Finding the zero line and the origin is shown on the figure 7.
Z1, Z2, Z3 and Z4 points;
It is marked as Zmax-Z2=Z1-Zmin=e and Zmax-Z4=Z3-Zmin=E.
The distances corresponding to the differences between the abscissas;
X3-X4=l, X3-X2=m, X1-X3=n ve X1X2=X3X4
will be marked.
The intersection of the horizontal line connecting the X2 and X3 points with the Z(0) line gives us the zero line, and the S(x) value on that line gives us the origin point.

Calculation of Welding Parameters

If the two characteristic ratios found are A and D, A≥D, the figure 4 is marked on the dyke model nomograms, and the figure 5 is marked on the fault model nomograms if A≤D, and the R and Q values where they intersect are read. Using the R and Q values, the parameters of the structure giving the anomaly are found from the analytical relations given below.
Calculation of depth and width for dyke model;
The upper level depth h of the dyke can be found with the equations (25) and (26) below [7].

$$H=0,5/[(XM.Xm).\tan Q] \quad (25)$$

$$h=[(XM.Xm)/(1+R^2/4)]^{1/2} \quad (26)$$

Taking the average of the two results from these two relations given above gives a healthier result.
The width of this dyke is;

$$2b=R.h \quad (27)$$

found from the relation. Since Q has only a value between 0° and 90° from the nomograms, the true value of Q can be found from the following criteria. In the anomaly curve,

If the positive anomaly is dominant and on the positive X-axis side, Q=Qn ya da Qn -360°
If the positive anomaly is dominant and on the negative X-axis side, Q=-Qn or -(Qn +360°)
If the negative anomaly is dominant and on the positive X-axis side, Q=Qn -180°
If the negative anomaly is dominant and on the positive X-axis side, Q=-(Qn +180°).
Qn is the Q value read from the nomograms.
Plumbing Angle: Since the index parameter Q was found before, the dip angle φ of the dyke or vertical fault is found from the equations (total, vertical, horizontal) given in Table 1 [7].

Area Work Kerkenes (Lost City of Pteria)

The first surface research works in the Kerkenes Mountain Ancient City, located in the Şahmuratlı Village of the Sorgun District of Yozgat Province in Turkey, started in 1993 and turned into a participatory research with the museum in 1998-2000. Excavations and researches have continued under the direction of British national Dr. Geoffrey Summers since 2001. is doing. Although it is estimated that the city was founded by the Medes during the Iron Age around 600 BC, the discovery of Phrygian inscriptions during the 2003 excavation season also indicates that the city may be a Phrygian settlement. The city's fortification walls, which are about 7 kilometers long, form a settlement area of 2.5 square kilometers. It is thought that the city recorded as Pteria in ancient sources is here. B.C. The city was captured by the Persians in 547, its people were captured, the city was burned and its walls were demolished. The residential area includes public buildings and civil building blocks and an advanced water collection and use system. They have completed some of the magnetic, resistivity studies from geophysical methods [10].

Geographical Status of the Region

Kerkenes, which is the research area, is within the borders of Yozgat province and is located on the touristic route between Hattusa (Bogaz castle) and Cappadocia (Figure 8). The region is located on Kerkenes Mountain, a granite mass located at the northern end of the Cappadocia plain, near Şahmuratlı Village, 12 km south of Sorgun District of Yozgat province. The city and the walls were built on the Kerkenes Mountain, which is at an altitude of 1,500 m topographically. It was obtained by combining two sheets with a scale of 1/25.000 obtained from MTA belonging to the study area [5].

Figure 8: Geographical location of Yozgat province in Turkey

Topography of The Region

A few thousand years ago, Kerkenes Mountain is thought to have resembled the rocky areas of the surrounding granite hills and sandy soil today. The vegetation, which was different from today's, also prevented the erosion of the soil. However, the influence of humans in the region and the subsequent settlement caused destruction by changing the morphology of this area very quickly. The basic elements necessary for the establishment of a big city are the strategic position, the natural defense system and a continuous water source. Topography played a very important role in the planning and construction of the city. City walls made of stone from local outcrops were built along the ridges. Most of the residential areas have been made usable by terracing the steep slopes and smoothing the uneven areas. Artificial reservoirs have been made and natural ones have been developed to control the water. Some structures were built using stone, but the majority used a adobe masonry system supported by wooden pillars placed on stone ground (Figure 9). The adobe bricks were made using sandy granitic soil [5].

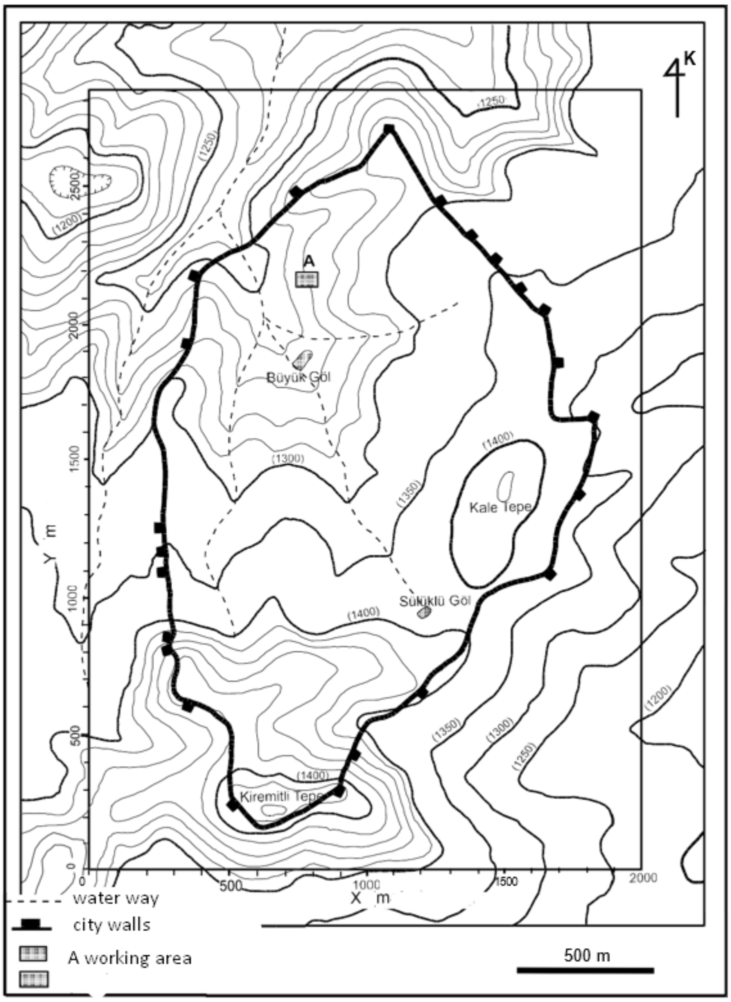

Figure 9: Topography map of the study area [5]

Geology of the study area

The granitic rocks that make up the Kerkenes Mountain have formed impressive outcrops. The magmatic, metamorphic and ophiolitic rocks cropping out in the east and southeast of Ankara in Central Anatolia, located on the Alpine-Himalayan mountain range, were named the Central Anatolian Crystalline Complex [11]. This complex has been severely fragmented due to continuous deformation since the Upper Cretaceous [12]. The Yozgat batholith located on the northern edge of the complex consists of granitic rocks and covers an area of approximately 750 km^2 (Figure 10). Bubatolite is divided into several different subunits. The walls and ruins of Kerkenes lie within the Kerkenes granitoid, which is the northeastern subunit of the Yozgat batholith. Although the Kerkenes granitoid, which covers an area of approximately 130 km^2, is mainly composed of hornblende-biotite granites, other types of granitic rocks can also be found [5].

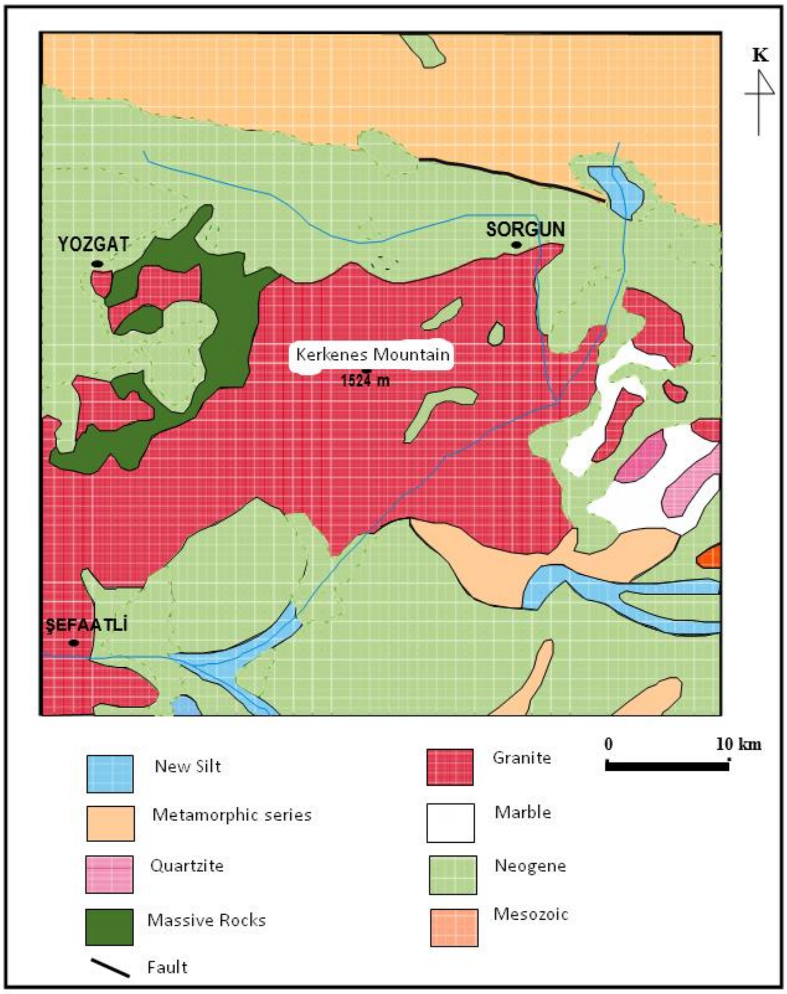

Figure 10: Simplified geological map of the study area

Geophysical Study

Magnetic study was carried out in the A region shown in the topographic map given in Figure 9. by the Kerkenes Excavation team; The underground remains were tried to be revealed in detail by measuring with two Geoscan FM 36 fluxgate gradiometers. In order to distinguish the iron age remains from the bedrock and the late period cultural remains, measurements were taken at intervals of 0.25 m along the profile in the x direction and 1 m along the profile in the y direction in units measuring 20 x 20 m. The Geoscan FM 36 flaxgate gradiometer used in the study area is a preferred tool for the determination of shallow underground structures, cultural remains, especially burned structures such as furnaces, furnaces, and clay. It is ideal with its capacity that can take 8 measurements per meter quickly. Such rapid measurements need to be done precisely. The sensitivity of the FM 36 flaxgate gradiometer can be reduced to 0.05 nT. Anomaly map obtained by Geoscan FM 36 fluxgate gradiometer in this region is given in figure 11. The anomaly of the AA' section obtained from the magnetic anomaly map given in Figure 11 is given in Figure 12.

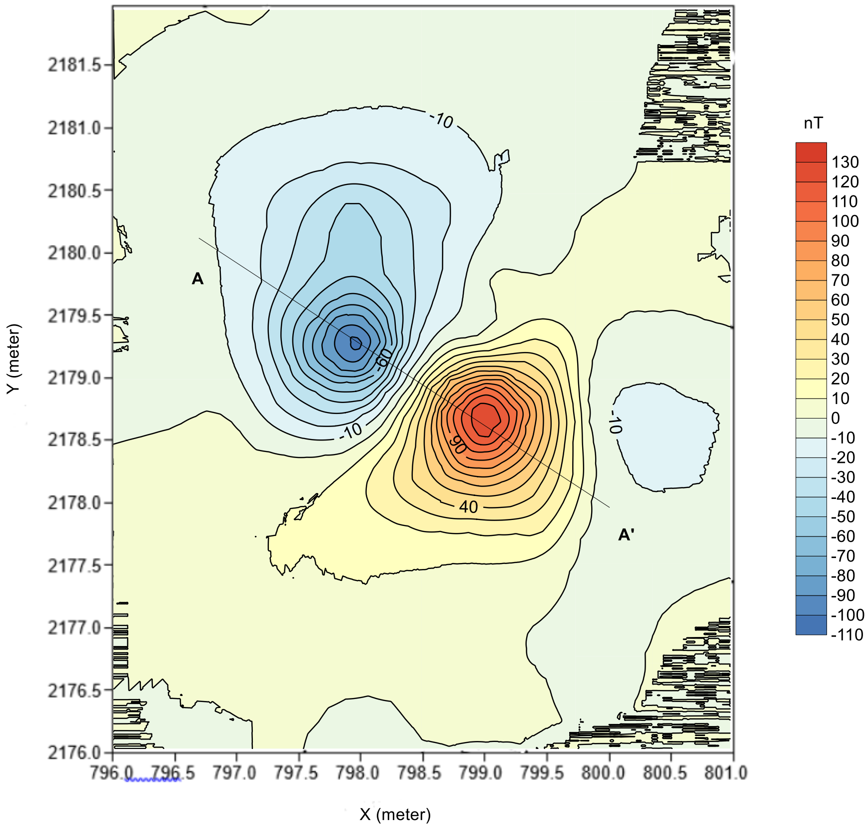

Figure 11: Magnetic anomaly map.

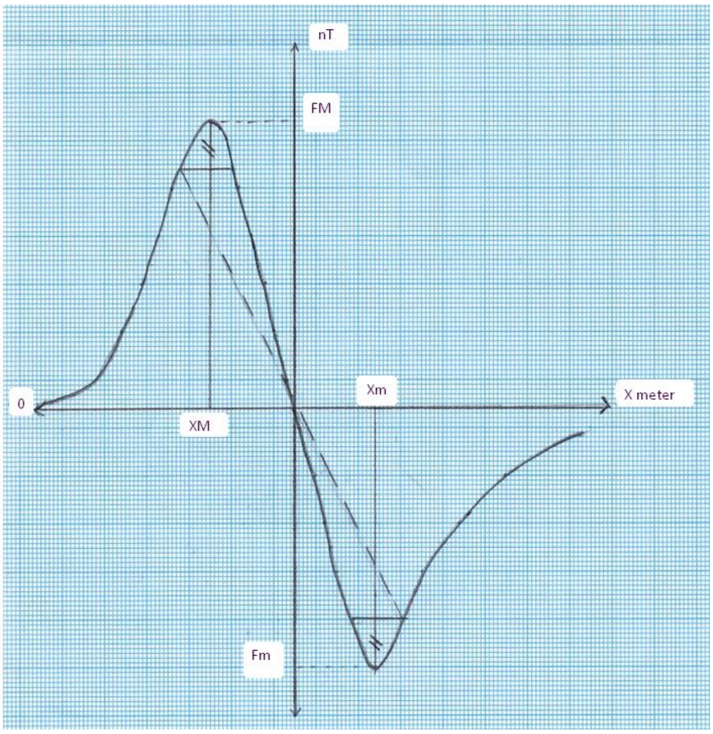

Figure 12: Magnetic anomaly of the AA' section.

Conclusion

It is known that interpretation methods based on a few characteristic points on the anomaly curve do not give good results when the characteristic points are incorrectly defined or when noises from environmental features overlap. However, these methods are faster than the classical curve fitting methods and give surprisingly good results in many cases. The smallest mistake to be made here is reflected in the results. Also, the method is useless since the anomaly curve is anti-symmetrical here. Because in this case, the ratios A and D to θ=90° approach zero. Therefore, it is not possible to find a single solution for R using these nomograms.

By using this method, information about the depth and width of the following structure can be obtained. It can also be understood whether the mass belongs to the dyke, fault or thin plate family. The method is very practical, applicable to total horizontal and vertical component anomalies.

The characteristic A and D ratios stated in the theoretical part over the anomaly were found to be 0.06 and 0.05, respectively. Since the anomaly curve F(x) is A>D, it belongs to a dyke family. Using the nomogram given for the dyke model, R=2.5 θ=87° was found. Using the related relations on the nomogram, the upper surface depth was calculated as h=19.08 meters and the half width of the dyke was calculated as b=23.85 meters.

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