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Determination of Horizontal Locations and Depths of Magnetic Sources Using Continuous Wavelet Transform

Sürekli Dalgacık Dönüşümü Kullanılarak Manyetik Kaynakların Yatay Konumlarının ve Derinliklerinin Belirlenmesi

Bülent ORUÇ
Kocaeli Universitesi, Mühendislik Fakültesi, Jeofizik Mühendisliği Bölümü Umuttepe Yerleşkesi, 41380 İzmit-Kocaeli

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ABSTRACT

This paper outlines the effects of resolution of magnetic anomaly data with continuous wavelet transform (CWT) technique. Using complex wavelets to analyze magnetic data allows us to find the position of buried sources for different inclination of their induced magnetization vector in scale space domain. The CWT local modulus maxima of wavelet coefficients of magnetic field data exhibit cone like structures for isolated and extended bodies. Thus, the modulus maxima lines of the coefficients (ridges of wavelet transform) are used to find location and mean depths of anomalous sources. First, I summarize the theory, which primarily consists of interpreting magnetic fields via the properties of the upward continued derivative field with the application shown on synthetic magnetic data and finally, the technique has been applied to the total field magnetic anomaly from Kesikköprü (Bala-Ankara) iron bed. I have also compared the CWT solutions with the results from Euler deconvolution (ED). The iron bed was estimated at a depth of about 40 m from both techniques.

Anahtar Kelimeler: Magnetic anomalies, continuous wavelet transform, local maxima, source position

ÖZ

Bu çalışma sürekli dalgacık dönüşümü (CWT) tekniği ile manyetik anomali verilerinin çözünürlüğündeki etkilerini açıklamaktadır. Manyetik verileri analiz etmek için kullanılan karmaşık dalgacıklar, ölçekleme ortamında, indükleme ile kazanılmış mıknatıslanma doğrultusunun farklı doğrultuları için gömülü kaynakların yatay lokasyonlarını belirlemede kullanılır. Manyetik alan verilerinin dalgacık katsayılarının CWT yerel genlik maksimumları, sonlu ve uzanım gösteren kütleler için konik özellkiler sunar. Böylece, katsayıların genlik maksimum çizgileri (dalgacık dönüşümünün sırtları), anomali kaynaklarının ortalama konumlarını ve derinliklerini bulmak için kullanılabilir. Çalışmada ilk olarak, yukarı uzanımın türev özellikleriyle yöntemin manyetik alan verilerini yorumlamadaki temel ilkeleri ele alınmıştır. CWT tekniği, Kesikköprü (Bala-Ankara) bölgesi demir cevherinin toplam alan manyetik anomalisine uygulanmıştır. Aynı veriye uygulanan Euler dekonvolüsyon tekniğinden elde edilen sonuçlarla CWT çözümleri karşılaştırılmıştır. Her iki teknikten cevher yatağı yaklaşık 40 m derinlikte belirlenmiştir.

Keywords: *Manyetik anomaliler, sürekli dalgacık dönüşümü, yerel maksimumlar, kaynak konumu*

B. Oruç
e-posta: bulent.oruc@kocaeli.edu.tr

INTRODUCTION

Magnetic data play an important role in the study of subsurface modeling because of the susceptibility contrasts in the subsurface. Magnetic surveys for environmental applications are usually employed to detect buried metallic sources in the investigation of mining area. In most mining applications, especially in shallow surveys, a simple interpretation of the maps allows one to localize the main metallic features in the subsurface. Data processing with enhancement procedure can substantially improve the reliability of magnetic surveys. Many different approaches are commonly used to analyze information regarding the source depth and locations.

Most of the methods such as Werner deconvolution (Hartman *et al*., 1971), the analytic signal (Nabighian, 1984; Roest *et al*., 1992) and the enhanced analytic signal (Hsu *et al.,* 1996, 1998) were essentially implemented to give an estimation of the depth to the sources. Thompson (1982) first presented the method known as ED which provides an information on the depth and other geometrical source parameters. The ED was extended to the analysis of maps by Reid *et al*. (1990). The source parameter imaging method was presented by Thurston and Smith (1997) and Smith *et al.* (1998). The same information as the ED by computing the so-called 'local wavenumber' was essentially obtained.

Holschneider (1995) has developed the wavelet transform (WT) as a powerful analysis tool. Then wavelets have become a significant research approach because of their large range of applications. Because wavelets are well localized in space and frequency, WT are used in a wide range of applications in signal processing. In Potential field analysis it was used to locate and characterize homogeneous causative sources point in 1D (Moreau et al, 1997). The methods based on the CWT have becoming a very useful tool in geophysics (Kumar and Foufoula-Georgiou, 1997; Hornby *et al*., 1998; Sailhac et al., 2000; Ouadfeul, 2006; Ouadfeul and Aliouane, 2010).

I have explored one-dimensional CWT of total field anomaly data in determining the horizontal location and depth of 2-D anomalous sources for various magnetization vectors. The CWT has been applied to dipping contact, semi-infinite vertical thick dike, semi-infinite dipping thin dike, infinitely horizontal cylinder, and smaller and shallower objects then illustrated by applications to total field anomaly data from Kesikköprü (Bala-Ankara) iron deposit.

Continuous Wavelet Transform (CWT)

There are two major approaches to WT. These are the CWT and the discrete wavelet transform (DWT). The CWT is implemented on a continuous range of dilatations and translations. The DWT, an orthogonal transformation, uses a dyadic set of dilatations and translations. In this study I use only the CWT for its redundancy which can be an advantage because it allows a fine analysis of the observed signal. However the CWT implies a great computational cost and large sets of coefficients to be manipulated.

Moreau et al. (1997) has defined that the CWT of a function f(x) can be expressed as convolution product with the mother wavelet as

$$W_{\psi|f}(b,a) = \int_{-\infty}^{\infty} \frac{1}{a}\psi\left(\frac{x-b}{a}\right) f(x)dx \\ = (D_a\psi * f)(b) \qquad (1)$$

where ψ is analyzing wavelet (or mother wavelet), a is dilation, b is translation and the dilation operator D_a is defined as

$$D_a\psi(x) = \frac{1}{a}\psi\left(\frac{x}{a}\right) \qquad (2)$$

Moreau et al. (1997, 1999) have shown that a special class of wavelets is obtained when a derivative of order γ and dilation are applied to the Poisson semi-group kernel. This kernel defines the continuation filter $P_a(x)$ which transforms the harmonic field from measured level z to the level z+a

$$P_a(x) = \frac{1}{\pi}\frac{a}{a^2 + x^2} \qquad (3)$$

Horizontal and vertical wavelets are defined as;

$$\psi_x^{\gamma}(x) = \frac{\partial^{\gamma}}{\partial x^{\gamma}}\left(\frac{1}{\pi}\frac{1}{1+x^2}\right) \quad (4)$$

and

$$\psi_z^{\gamma}(x) = \frac{\partial^{\gamma-1}}{\partial x^{\gamma-1}}\frac{\partial}{\partial a}\left(\frac{1}{\pi}\frac{a}{a^2+x^2}\right)\Bigg|_{a=1} \quad (5)$$

A complex wavelet is defined as:

$$\psi_c^{\gamma}(x) = \psi_x^{\gamma}(x) - i\,\psi_z^{\gamma}(x) \quad (6)$$

The complex wavelet transform of the potential field f(x) is given by

$$W_{\psi_c^{\gamma}|f}(x,a) = W_{\psi_x^{\gamma}|f}(x,a) - iW_{\psi_z^{\gamma}|f}(x,a). \quad (7)$$

Moreau et al. (1997, 1999) have showed that positioning of maxima of the modulus of the CWT at scale a is equivalent to a combination of derivation/upward continuation of the field at the depth level z=a.

Theoretical Examples

The following examples illustrate the application of the technique on the magnetic anomaly due to isolated and extended homogeneous magnetic sources. The examples demonstrated could correspond to the case of zero remanent magnetization, with all magnetization being induced. To understand the behaviour of the modulus maxima of CWT of the magnetic anomaly due to the anomalous sources, I present the CWT analysis for various field inclinations. The first example is shown in Figure 1 to analyze the magnetic anomaly due to a dipping contact at the upper and bottom depth of 10 m and 40 m (Figure 1a, 1b, 1c and 1d), horizontal location of 100 m. The wavelet coefficients are computed by applying CWT to the anomaly using Poisson semi-group kernel.

Figure 1a and 1b show the calculated values of CWT coefficients for different dilations (1-100) of magnetic anomaly. The maxima of modulus of CWT provide cone like structures and are clearly shown which points towards the position of the upper corner of the model. On the other hand, whereas an approximate horizontal location has been estimated, an intersection of modulus maxima lines in the subsurface has placed on the upper depth of the model. However, the maxima of modulus of CWT does not provide cone like structures and the subsurface position of the model has not therefore obtained since magnetization direction is not vertical direction. Meanwhile, to determine precisely where the modulus maxima lines corresponding to intersections the abscissa, a least squares line fitting algorithm has been employed. To this end, the algorithm has been proceeded to the maxima of modulus by ignoring the extreme points. This algorithm proceeds to all theoretical and real examples.

Figure 2 shows the magnetic anomaly due to an infinitely horizontal cylinder at the depth of 30 m, horizontal location of 100 m and radius of 10 m, magnetization inclination of 60 degree, and declination of 3 degree. The wavelet coefficients are computed by applying CWT to the anomaly using Poisson semi-group kernel. Figure 1 shows the calculated values of CWT coefficients for different dilations (1-50) of magnetic anomalies. The cone like structure is clearly shown which points towards the position of the center of horizontal cylinder although intersection of the modulus maxima lines in the subsurface has been slightly shallower than depth to center of the model.

I have analyzed the CWT of the magnetic anomaly due to a semi-infinite dipping thin dike at the depths of 10 m and 20 m (Figure 3 a and 3 b). The wavelet coefficients are computed by applying CWT to the using Poisson semi-group kernel. Figure 3 a and 3 b show the calculated values of CWT coefficients for different dilations (1-60) of magnetic anomaly. The cone like structure is clearly shown which points towards the location of the source. It should be noted that main feature of the modulus maxima from magnetic anomaly due to thin dike model is that it yields much more successful depth-to-top.

Figure 4 shows the application of technique on semi-infinite vertical thick dike. The CWT

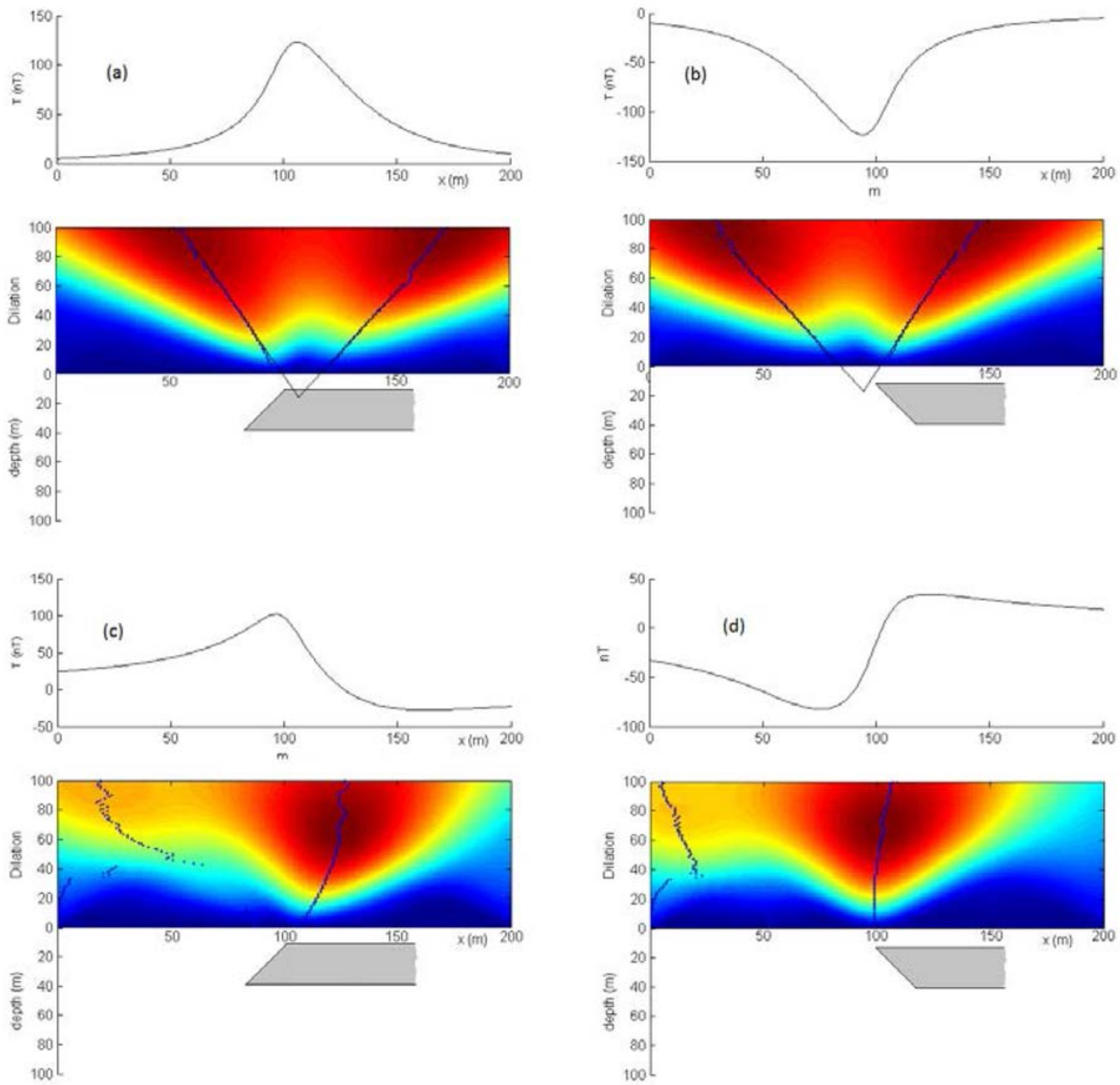

Figure 1. The modulus of CWT coefficients at different dilations (1-100) and distances (0-200 m) of total field magnetic anomaly caused by a dipping contact model to depth of the upper and bottom of 10 m and 40 m, respectively. Sampling interval is 1 m. Inducing field has an assumed strength of 47000 nT, susceptibility 0.001. a) The magnetization has an inclination of 90° and a declination of 0°. The dip angle of the model is 135°. b) The magnetization has an inclination of 90° and a declination of 0°. The dip angle of the model is 45°. c) The magnetization has an inclination of 60° and a declination of 3°. The dip angle of the model is 135°. d) The magnetization has an inclination of 60° and declination of 3°. The dip angle of the model is 45°

Şekil 1. Üst derinliği 10 m, alt derinliği 40 m olan dalımlı kontak modelinin toplam alan manyetik anomalisinin, farklı ölçekleme (1-100) ve uzaklıklarda (0-200 m) CWT katsayılarının genliği. Örnekleme aralığı 1 m dir. Alan şiddeti 50000 nT ve süseptibilite 0.001 olarak kabul edilir . a) Mıknatıslanma vektörünün inklinasyon açısı 90° ve deklinasyon açısı 0°. Modelin dalım açısı 135°. b) Mıknatıslanma vektörünün inklinasyon açısı 90° ve deklinasyon açısı 0°. Modelin dalım açısı 45°. c) Mıknatıslanma vektörünün inklinasyon açısı 60° ve deklinasyon açısı 3°. Modelin dalım açısı 135°. d) Mıknatıslanma vektörünün inklinasyon açısı 60° ve deklinasyon açısı 3°. Modelin dalım açısı 45°.

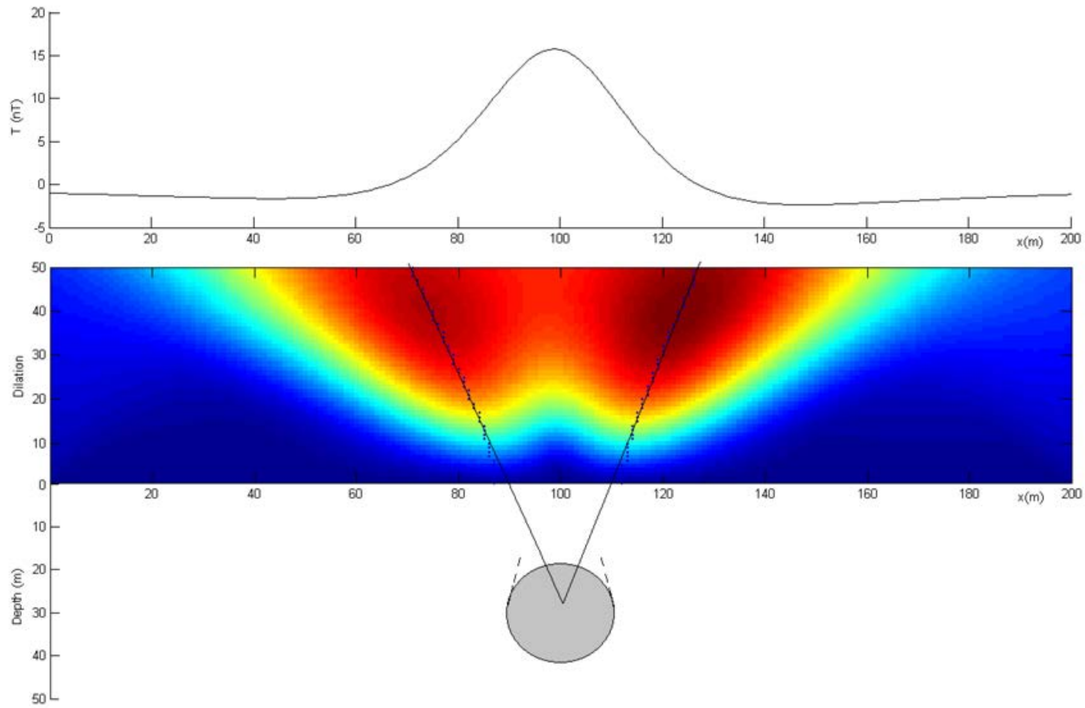

Figure 2. The modulus of CWT coefficients at different dilations (1-50) and distances (0-200 m) of total field magnetic anomaly caused by a long horizontal cylinder at the center depth of 30 m. Sampling interval is 1 m. Inducing field has an assumed strength of 45000 nT, susceptibility 0.001, and an inclination of 45° and a declination of 3°.
Şekil 2. Merkez derinliği 30 m olan uzun yatay silindir modelinin toplam alan manyetik anomalisinin, farklı ölçekleme (1-50) ve uzaklıklarda (0-200 m) CWT katsayılarının genliği. Örnekleme aralığı 1 m dir. Alan şiddeti 45000 nT , süseptibilite 0.001, inkilasyon 45° ve deklinasyon 3° olarak kabul edilir.

coefficients have been calculated for theoretical magnetic anomaly due to thick dikes placed at 100 m and depth of 10 m and 20 m. Figure 4 a and 4 b shows the results of CWT analysis for magnetization vector of 60° and 90°, respectively. In this case modulus maxima lines do not converge to the top edges of dikes for 60°. However, modulus maxima lines converge to the top edges of dikes for 90° giving horizontal location of 100 m and depth of 10 m and 20 m (Figure 4 c and 4 d). Hence, it is clear that the CWT technique could be valid for the vertical magnetization direction for thick dike model.

The CWT is analyzed to test the effect of interfering narrow objects at the shallower depths. The magnetic anomaly (Figure 5) of two polygonal models has been calculated using a method given by Won and Bevis (1987). As is well known, interfering anomalies have been a problem in that their interpretation is complicated. Note that the modulus maxima lines converge the depth to the bottom edge of the deeper one and center of the shallower one. In addition, it can be seen that the exact horizontal location has been obtained, whereas the method yields the mean depths for small and shallower bodies. In addition, there is an important feature related to the skewness of anomaly and CWT modulus. Depending on the source depth, the image of CWT modulus is stronger and more pronounced when strength and sharpening of the anomaly increase (Figure 5).

Application on real data

Figure 6 a shows a widespread magmatic intrusive associations intrude the crustal metamorphic rocks of the Kırsehir block (Görür et al,

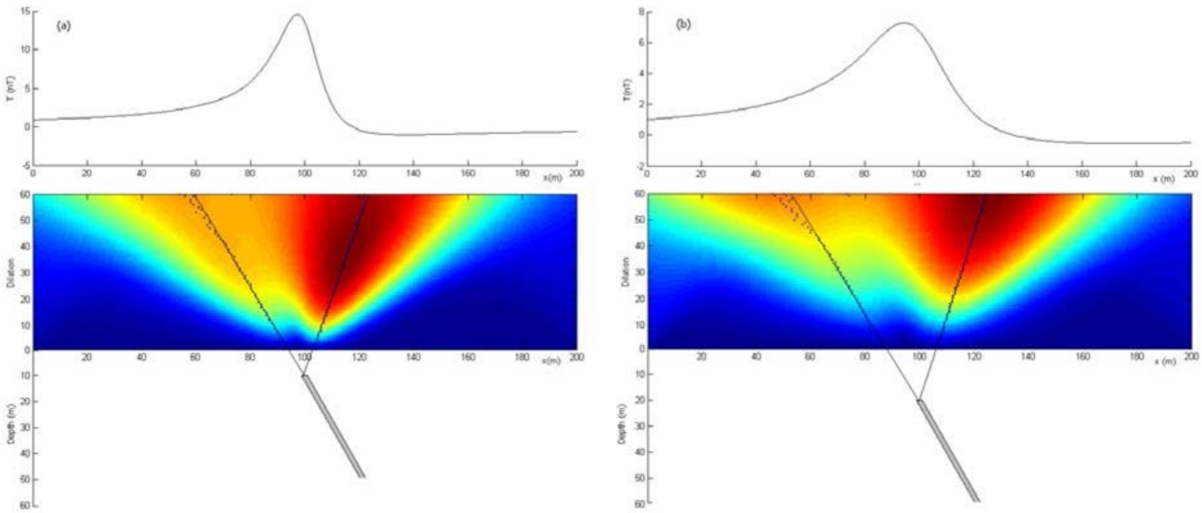

Figure 3. The modulus of CWT coefficients at different dilations (1-60) and distances (0-200 m) of total field magnetic anomaly due to semi-infinite dipping thin dike models to the depth of 10 m. Sampling interval is 1 m. Inducing field has an assumed strength of 45000 nT, susceptibility of 0.001 and a magnetization inclination of 60° and declination of 3°. a) The model to the top of the depth is 10 m. b) The model to the top of the depth is 20 m.

Şekil 3. Yarı sonsuz ince dayk modellerinin toplam alan manyetik anomalisinin,farklı ölçekleme (1-50) ve uzaklıklarda (0-200 m) CWT katsayılarının genliği. Örnekleme aralığı 1 m dir. Alan şiddeti 45000 nT, süseptibilite 0.001, inkilasyon 60° ve deklinasyon 3° olarak kabul edilir. a) Model derinliği 10 m. b) Model derinliği 20 m.

1984) or Central Anatolian Crystalline Complex (Göncüoglu et al., 1991). The study area is on the western edge of the Central Anatolian Massif (Figure 6 a). The basement in the vicinity of study area comprised by rock assemblages of Kırşehir massive is overlain by the upper Cretaceous ophiolitic complex together with sedimentary and volcanic-volcaniclastic rocks.

Examination of mineral deposits in the Central Anatolian Crystalline Complex provides broad new insights regarding their genesis. Considering their regional distribution and relationship to the geologic evolution of the region, the skarn and vein deposits constitute an important part of the metallogeny of the Central Anatolian Crystalline Complex (Kuşcu and Erler, 1998). Kesikköprü Iron Bed is one of the important iron mineralization in central Anatolia. In this area, the skarn-type iron deposits developed immediately adjacent to granitoid contacts.

Magnetic anomaly data provided by the General Directorate of the Mineral Research and Exploration Company of Turkey (MTA) have been compiled from Kesikköprü region. The total field magnetic anomaly map is shown in Figure 6 b.

CWT Analysis of Magnetic Data of Kesikköprü iron bed

For the present study I interpret an anomaly of 121 m length along the profile, AA'. I have digitized the profile a spacing of 0.3 m (Figure 7). The CWT analysis carried out on Figure 6 b using the Poisson semi-group kernel for 1-50 scaling. Although cone like structure in CWT modulus occurs, the modulus maxima do not converge towards the location of the source. In order to overcome this problem, the reduction to pole (RTP) process has been applied to the profile. As well known, RTP, which reduces the effect of the Earth's ambient magnetic field and provides a more accurate determination of the poition of source bodies. Thus, recomputing

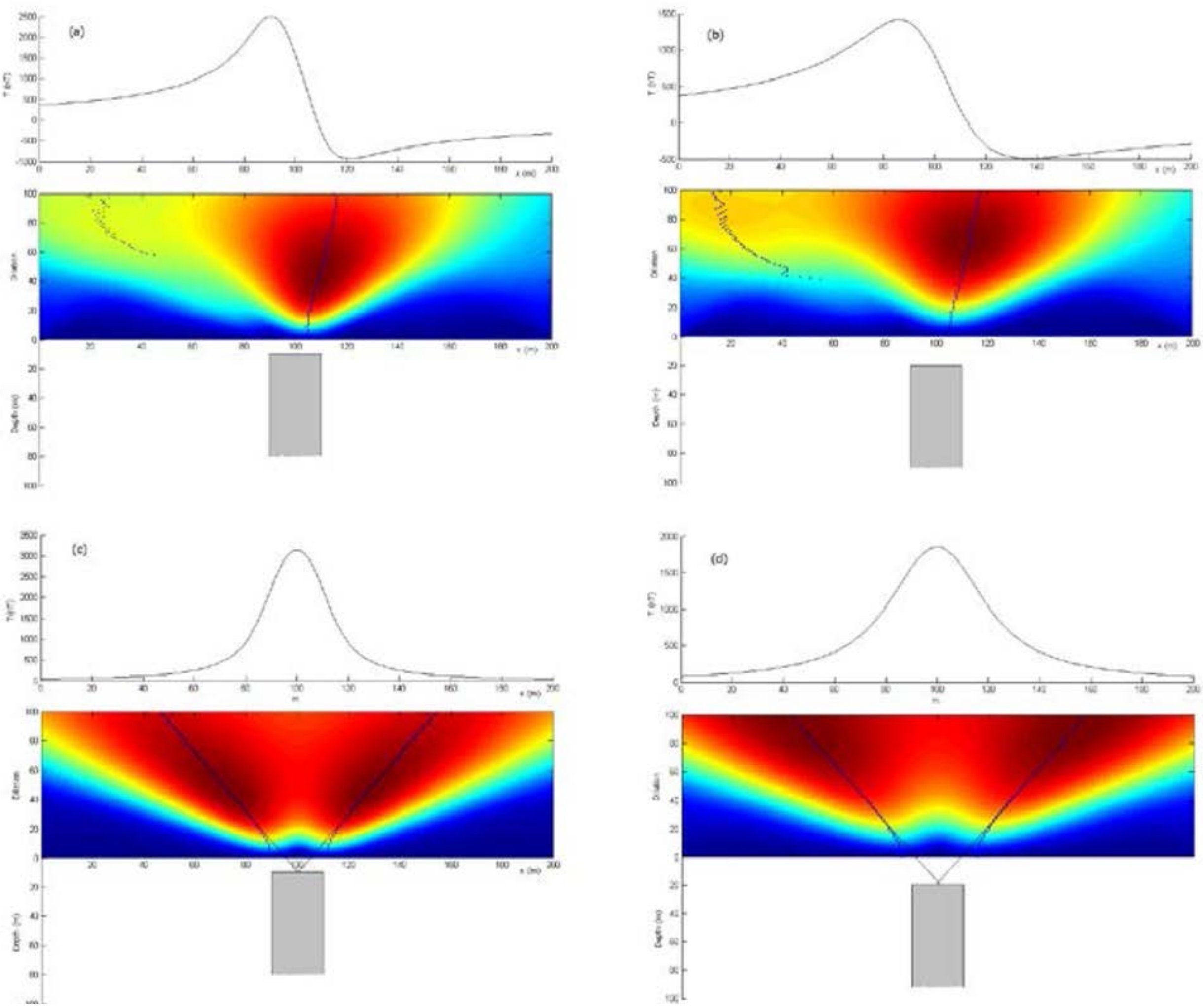

Figure 4. The modulus of CWT coefficients at dilations (1-100) and distances (0-200 m) of magnetic anomalies due to semi-infinite vertical dikes with the depth of top of 10 m and 20 m and the half width of 10 m. Sampling interval is 1 m. Magnetization has strength of 1000 A/m and declination of 3°. a) The model to the to the top of the depth is 10 m, and magnetization inclination is 60°. b) The model to the top of the depth is 20 m, and magnetization inclination is 60°. c) The model to the depth is 10 m, and magnetization inclination is 90°. d) The model to the depth is 20 m, and magnetization inclination is 90°.

Şekil 4. Üst derinlikleri 10 m, 20 m ve yarı genişliği 10 m olan yarı sonsuz düşey dayk modellerinin toplam alan manyetik anomalisinin, farklı ölçekleme (1-100) ve uzaklıklarda (0-200 m) CWT katsayılarının genliği. Örnekleme aralığı 1 m dir. Mıknatıslanma şiddeti 1000 A/m ve deklinasyon 3° dir. a) Model üst derinliği 10 m ve inklinasyon 60° dir. b)Model üst derinliği 20 m ve inklinasyon 60° dir. c) Model üst derinliği 10 m ve inklinasyon 90° dir. d) Model üst derinliği 20 m ve inklinasyon 90° dir.

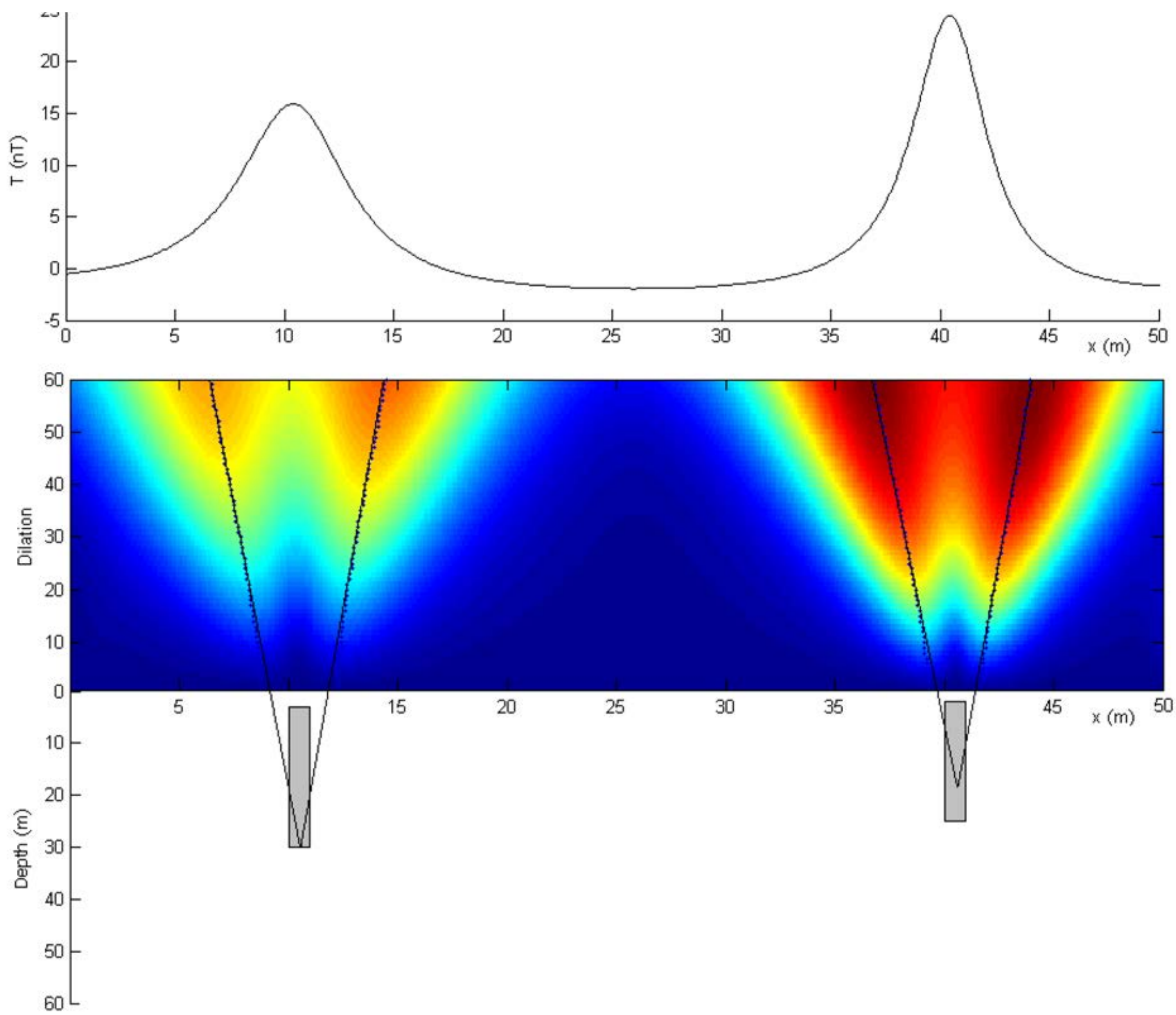

Figure 5. The modulus of CWT coefficients at different dilations (1-60) and distances (0-50 m) of total field magnetic anomalies due to shallower objects at the different locations and depths. Sampling interval is 0.1 m. Inducing field has an assumed strength of 47000 nT, susceptibility of 0.001, and magnetization inclination of 60° and declination of 3°.
Şekil 5. Farklı konum ve derinliklerde sığ kütlelerin toplam alan manyetik anomalisinin, farklı ölçeklemе (1-50) ve uzaklıklarda (0-200 m) CWT katsayılarının genliği. Örnekleme aralığı 0.1 m dir. Alan şiddeti 47000 nT, süseptibilite 0.001, inkilasyon 60° ve deklinasyon 3° olarak kabul edilir.

a magnetic field so it appears as it would at a magnetic inclination of 90 degrees (i.e. the magnetic North Pole). A constant direction of the magnetic field with declination of 4.1° and inclination of 56.2° was used for the area. The profile is reduced to the pole, assuming it to be entirely due to induced magnetisation, with no remanent component using the algorithm given by Gunn (1975). Then, as shown in Figure 8, when I compute the CWT of magnetic anomaly reduced to pole, the modulus maxima lines of cone-like structure are shown which point towards the position of the source at the abscissa at 60 m and depth of 42 m.

Comparison of ED with CWT results

According to Thompson (1982), the following relationship between the magnetic field

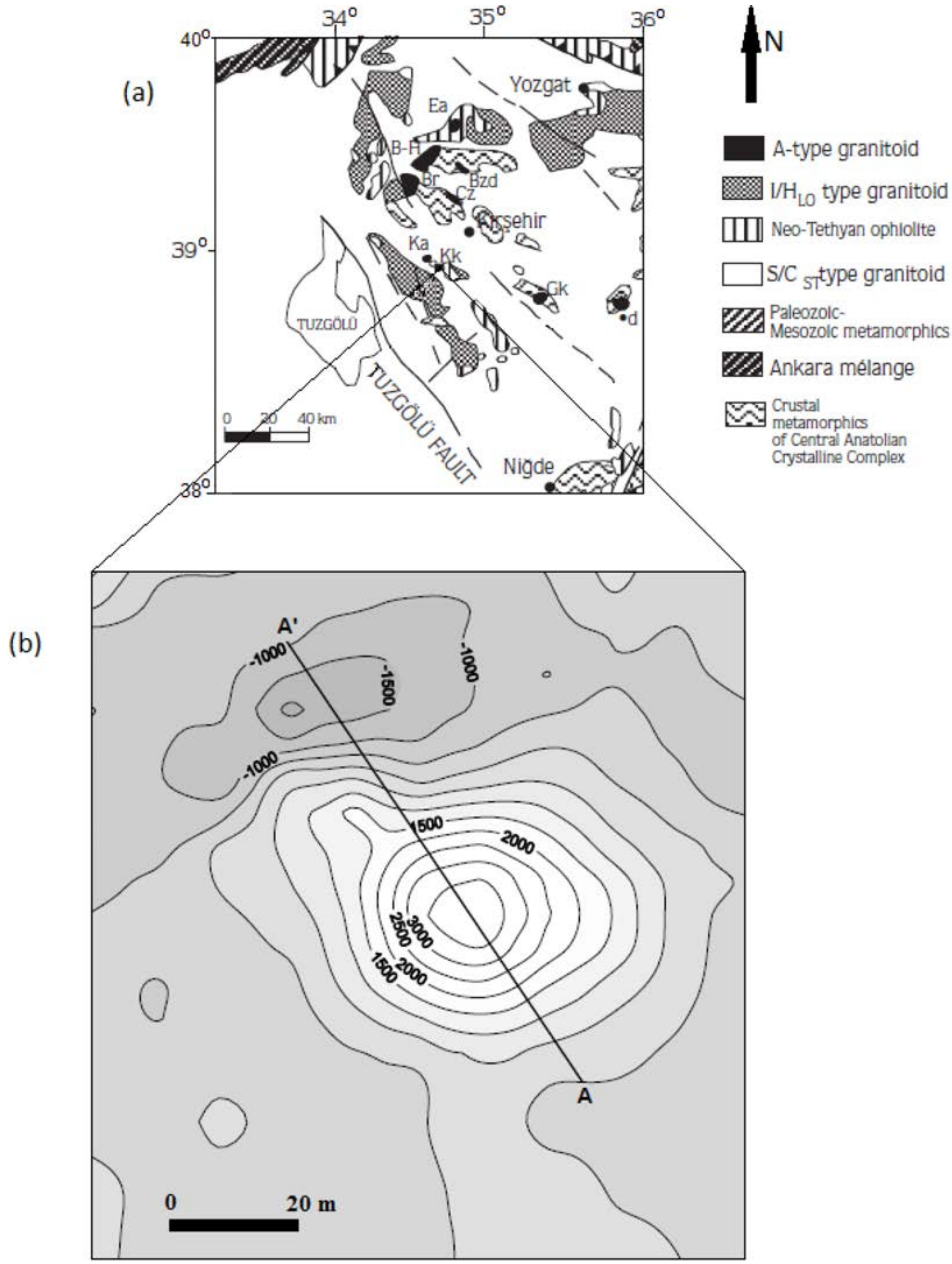

Figure 6. a) Simplified geologic setting a part of central Anatolia in Turkey (modified after Boztuğ, 1998). The abbreviations of plutons are as follow (from west to east): B-H, Bayındır-Hamit; Ea, Eğrialan; Br, Baranadag; Bzd, Buzlukdağ; Çz, Çayağzı; Ka, Kuruağıl; Kk, Kesikköprü; Gk, Gümüşkent; Id, Idişdağ. b)Total field magnetic anomaly map of Kesikköprü survey area (Aydın, 2008).

Şekil 6. a) Orta Anadolu'nun bir kesiminin basitleştirilmiş jeoloji haritası. (Boztuğ, 1998'den düzenlenerek) Plutonların kısaltlamar (Batı'dan Doğu'ya): B-H:Bayındır-Hamit; Ea:Eğrialan; Br:Baranadag; Bzd:Buzlukdağ; Çz:Çayağzı; Ka:Kuruağıl; Kk: Kesikköprü; Gk: Gümüşkent; Id: Idişdağ. b) Kesikköprü toplam alan manyetik anomali haritası (Aydın, 2008).

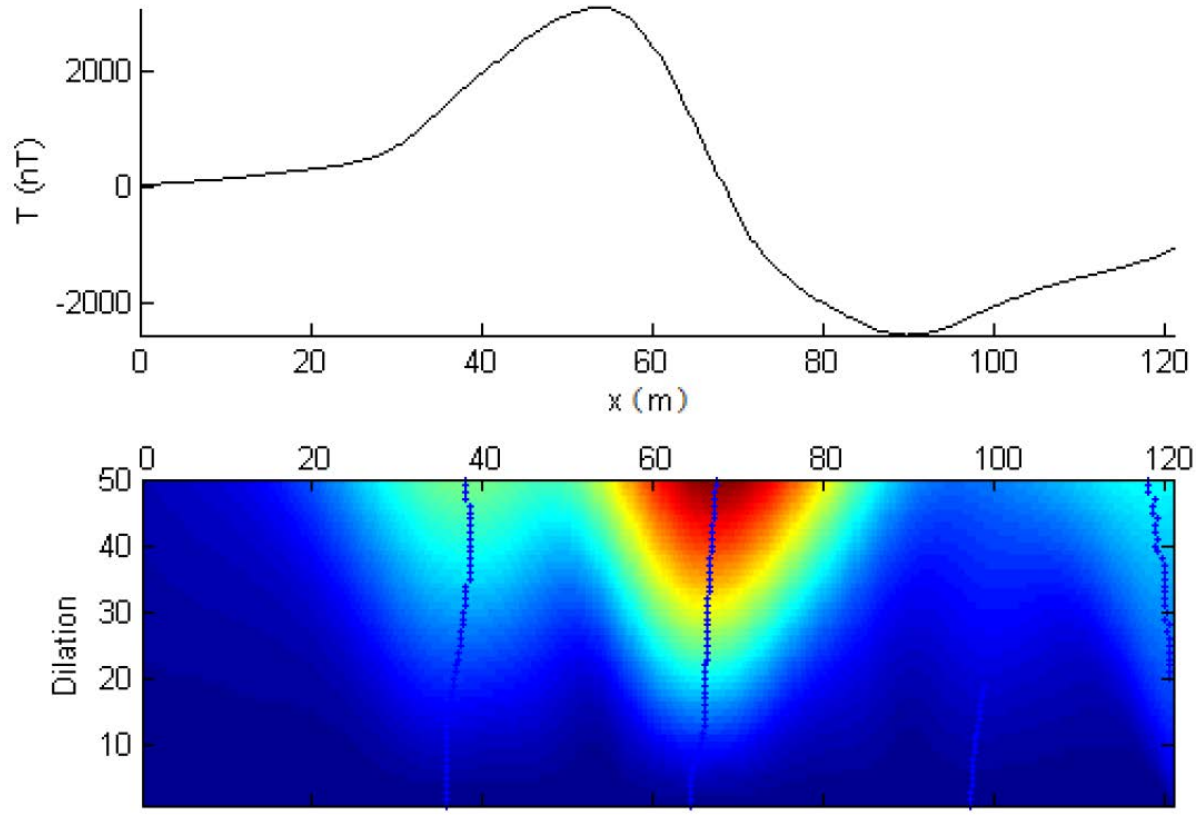

Figure 7. The modulus of CWT coefficients at different dilations (1-50) and distances (0-121 m) of Kesikköprü magnetic anomaly. Sampling interval is 0.3 m. It is clear that the modulus maxima do not converge towards the location of any source.

Şekil 7. Kesikköprü manyetik anomalisinin, farklı ölçekleme (1-50) ve uzaklıklarda (0-121 m) CWT katsayılarının genliği. Örnekleme aralığı 0.3 mdir. Genlik maksimumlarının kaynağa doğru yakınsamadığı açıktır.

intensity and the horizontal and vertical gradients yields (2D case):

$$x_0 \frac{\partial \Delta T(x)}{\partial x} + z_0 \frac{\partial \Delta T(x)}{\partial z} = x \frac{\partial \Delta T(x)}{\partial x} + N \Delta T(x) \quad (8)$$

where the derivatives can be measured or computed from the magnetic anomaly data: the unknown quantities of the equation are the coordinates x_0, the distance along the profile, and z_0, the depth of the magnetic source. The *N* value (structural index or briefly SI) represents the type of sources which best suited the anomaly. The SI is also a measure of the fall-off rates of the effect of each magnetic anomaly. For instance, a point dipole (sphere) has a typical structural index N=3, a line of dipoles (circular cylinder) N=2, thin dike N=1, semi-infinite dipoles (thin rod) N=2 and semi-infinite triangular plate (thin plate) N=1 (Stavrev, 1997).

The horizontal and vertical derivatives of RTP anomaly were calculated using FFT algorithm for the ED application. The ED has been applied to the magnetic anomaly reduced to the pole using a structural index N=1, 2 and 3 (Figure 9). A 7-point window is used to form simultaneous equations for the two unknowns (x_0, z_0), and solved these equations by a least squares method. Note the best clustering for source positions for N=3 indicate general trends associated with the horizontal location and depth obtained from CWT analysis in Figure 8. Thus,

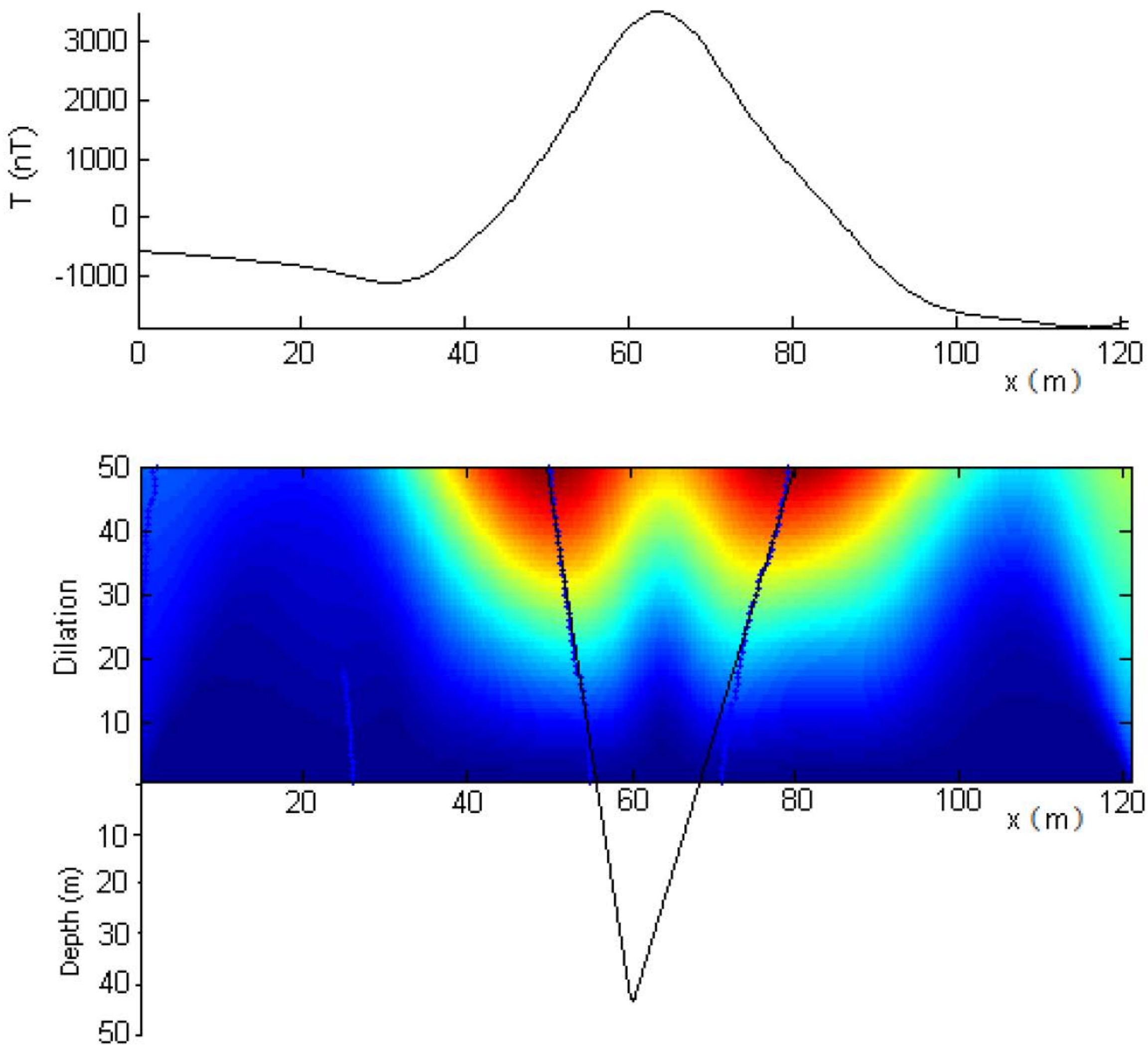

Figure 8. The modulus of CWT coefficients at different dilations (1-50) and distances (0-121 m) of reduced to pole data of magnetic anomaly in Figure 7. Sampling interval is 0.3 m. The modulus maxima lines converge towards the horizontal location of 60 m and depth of 42 m.

Şekil 8. Şekil 7'de manyetik anomalinin kutba indirgenmiş verisinin farklı ölçekleme (1-50) ve uzaklıklarda (0-121 m) CWT katsayılarının genliği. Örnekleme aralığı 0.3 mdir. Genlik maksimumları, 60 m yatay lokasyon ve 42 m derinlikte kesişmektedir.

these results could be interpreted as reflecting the presence of point dipole (sphere) which may be approximated prismatic body.

CONCLUSIONS

It has been shown that CWT allows estimating the position of the buried shallow-source anomalies and the deep-source ones. I have illustrated the experimental results that semi-infinite extended bodies (thin dyke, thick dyke and long horizontal cylinder) are fairly well-determined. For large dilations, the modulus maxima of the CWT of the magnetic anomalies contain the main features of the location and depth information of anomalous source in the magnetic anomaly data. In theoretical applications, the CWT modulus response of dipping contact, semi-infinite thin dyke, and long

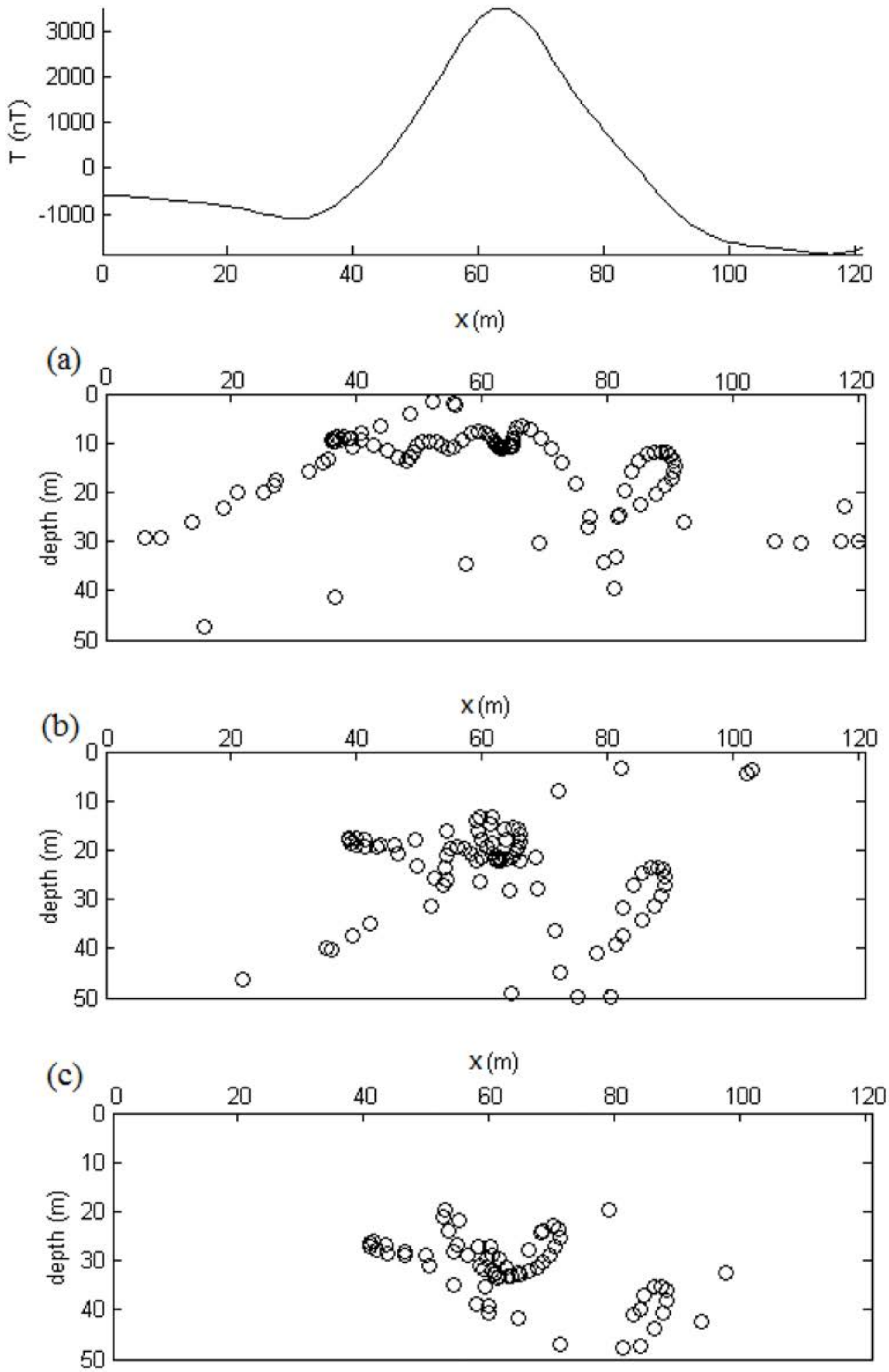

Figure 9. Results of ED with window size=7 by using different N values, (a) N=1, (b) N=2, (c) N=3. Note the clustering and stability of the depth solutions is most consistent for the N value of 3.
Şekil 9. Farklı SI değerleri ve pencere boyu 7 kullanılarak elde edilen ED sonuçları. a) N=1, b) N=2, c) N=3. Kümelenme ve derinlik çözümlerindeki duraylılığın N=3 değeri için elde edildiğine dikkat edilmelidir.

horizontal cylinder appear two cones pointing toward the upper and center depth (for cylinder) at small dilations. In addition, the position of semi-infinite thin dyke and long horizontal cylinder are independent of the magnetization direction except for semi-infinite thick dyke and dipping contact with a single conical pattern in CWT modulus. A satisfactory result of thick dyke and dipping contact model has been obtained in case the magnetization direction is vertical.

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Düzeltme (Erratum)

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