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THE USE OF TILT ANGLE IN GRAVITY AND MAGNETIC METHODS

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ABSTRACT.- Tilt angle method, which has been recently used in investigating the boundaries of structures, reveals useful information on deep and shallow structures. Tilt angle is expressed as the arctan value of the ratio of the vertical derivative of the potential field to its horizontal derivative. The method was applied to Kırşehir-İ31 sheet. As a result, the presence of volcanites buried under terrestrial sediments was demonstrated.

Key words: Magnetic, gravity, tilt angle, volcanic rocks, Kırıkkale.

INTRODUCTION

Tilt Angle Method was applied to 1: 100.000 scale Kırşehir-İ31 map sheet which is situated between 33°30'-34°00' longitudes and 39°30'-40°00' latitudes in the vicinity of Kırıkkale (Figure 1). The objective was to determine the subsurface location of the Late Cretaceous aged volcanic rocks in the study area using this method.

In potential field methods (gravity and magnetic) in the determination of the structural boundary of the body causing anomaly, there are a lot of methods such as analytic signal, horizontal derivative, first and second vertical derivatives, Euler deconvolution, artificial gravity, Normalized Full Gradient (NFG). Cordell and Grauch (1982, 1985) studied the magnetization or horizontal variations in density of the upper crustal rocks. Blakely and Simpson (1986) improved the works of Cordell and Grauch and carried out a study which reveals the boundaries of the source body by means of magnetic and gravity anomalies.

Hood and Teskey (1989) and Roest et al. (1992) investigated vertical boundaries of body using horizontal and vertical derivatives. Thompson (1982) made depth estimation applying Euler equation to magnetic data.

With the aim of detection of oil deposits NFG method (Normalized Full Gradient Method) was applied to gravity data for the first time by Berezkin and Buketov (1965). In following years, the application of this method to magnetic data was realized by Berezkin et al. (1994). And in Turkey, Aydın et al. (1997) and Aydın (2000, 2007) applied this method to gravity and magnetic data. Furthermore, the method was used in seismic studies by Karslı (2001), in electromagnetic studies by Dondurur (2005) and in SP studies by Sındırgı et al. (2008).

Miller and Singh (1994) compared tilt angle with horizontal derivative, second vertical derivative and analytic signal techniques. Salem et al. (2008) developed new techniques to interpret magnetic data. By means of linear correlation, similar to 3D Euler equation, they evaluated tilt angle derivatives and calculated horizontal locations and vertical depths of bodies without using structural index.

TILT ANGLE

Tilt angle is defined as the arctan value of the ratio of the vertical derivative of the potential field to its horizontal derivative (Miller and Singh, 1994; Verduzco at al., 2004) as seen in figure 2.

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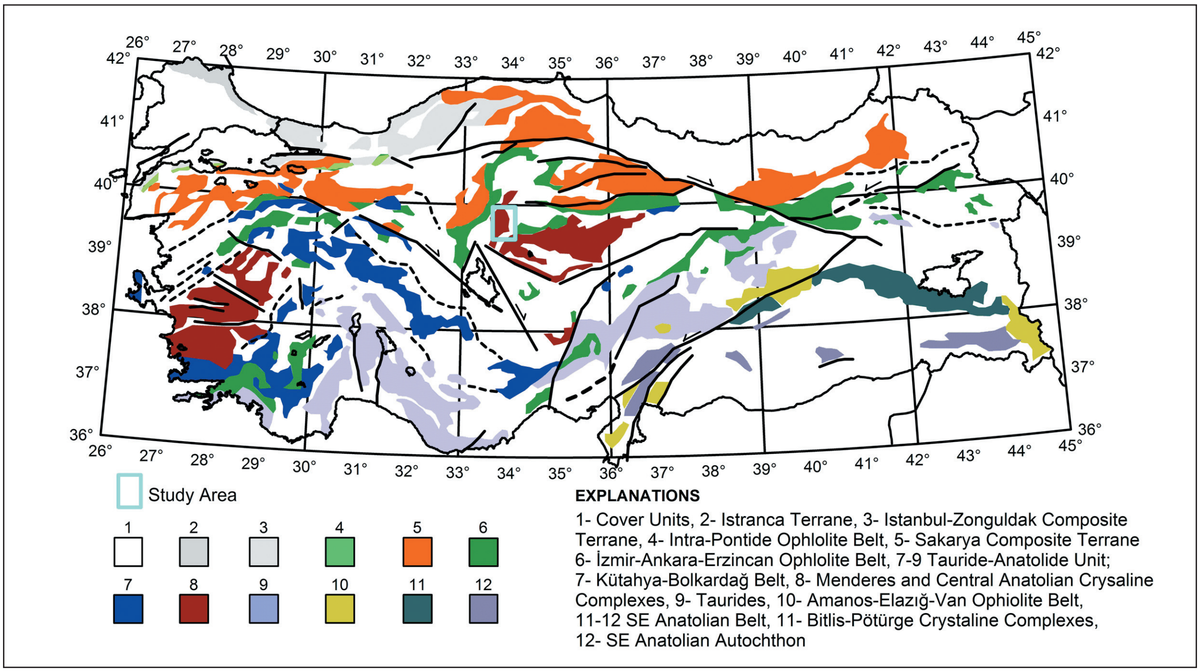

Figure 1- The location map and geological position of the study area in Turkey (Modified after Göncüoğlu et al. 1996).

Tilt angle;

$$\theta = tan^{-1}\frac{\left(\frac{\partial T}{\partial z}\right)}{\left(\frac{\partial T}{\partial h}\right)}$$

where

$$\frac{\partial T}{\partial h} = \left[\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2\right]^{1/2}$$

and $\partial T/\partial x$, $\partial T/\partial y$, $\partial T/\partial z$ are first - order derivatives of the potential field in the *x, y*, and *z* directions; $\partial T/\partial h$ is total horizontal derivative, θ is tilt angle, *T* is potential field.

Horizontal derivatives of potential field data were computed using finite differences relations. For example, at a grid point i,j ; the derivatives of a total magnetic field measurement value T (i,j) in the x and y directions are given as

$$\frac{\partial T}{\partial x} = \frac{T_{i+1,j} - T_{i-1,j}}{2\Delta X}$$

$$\frac{\partial T}{\partial y} = \frac{T_{i,j+1} - T_{i,j-1}}{2\Delta y}$$

The derivatives of the potential field data in the vertical direction can be computed in the frequency environment using the equation below (Gunn, 1975).

$$\frac{\partial^n T}{\partial z^n} = T(f)|f|^n$$

Here, T(f) shows the amplitude value in the f frequency, and n shows order of the derivative. In this study first-order derivatives in the vertical direction were computed (using n=1).

The advantage of the tilt angle method comparing to the other methods is that there is

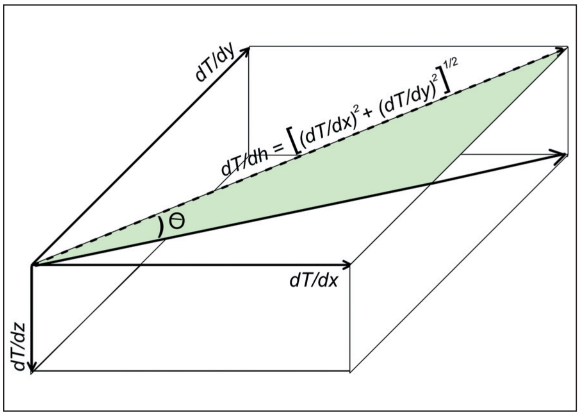

Figure 2- Geometric delineation of tilt angle (θ)

no need for parameters (density, magnetic susceptibility, inclination and deflection angles, permanent magnetization, structural index, etc.). An estimation can be made about the depth of the source from the contours of the tilt angle. Due to the nature of the arctan trigonometric function, all tilt amplitudes are restricted between -90° and +90°.

Miller and Singh (1994) showed the boundaries of the source body by means of tilt angle. As the part where the contours of the tilt angle are positive defines the source itself, the part where the contours are negative represents the outside of the source and the zero contour represents the vertical boundary of the source. For this reason, Miller and Singh (1994) stated that it is possible to obtain reliable results about structural boundaries by means of tilt angle method.

Salem et al. (2007, 2008) expressed the relationship between the upper depth (z_c) and horizontal location (h) of the source by means of a simple drawing.

According to Nabighian (1972) the horizontal and vertical derivatives of the magnetic field over contacts located at a horizontal location of h=0 and at a depth of z_c are given by the equations

$$\frac{\partial T}{\partial h} = 2KF_c\, sind\, \frac{z_c \cos(2I-d-90)+h \sin(2I-d-90)}{h^2+z_c^2}$$

$$\frac{\partial T}{\partial z} = 2KF_c sind\, \frac{h cos(2I-d-90)-z_c \sin(2I-d-90)}{h^2+z_c^2}$$

where

(K) is the susceptibility contrast at the contact, (F) the magnitude of the magnetic field,

c=1-cos^2$i$sin^{2}A,

(A) the angle between the positive h-axis and magnetic north,

(i) the ambient field inclination,

tanI=tani/cosA,

(d) the dip (measured from the positive h-axis) and all trigonometric quantities are in degrees.

Under certain assumptions such as when the contacts are nearly vertical and the magnetic field is vertical or reduced to the pole, last two equations can be written as

$$\frac{\partial T}{\partial h} = 2KF_c \frac{z_c}{h^2+z_c^2}$$

$$\frac{\partial T}{\partial z} = 2KF_c \frac{h}{h^2+z_c^2}$$

Substituting equations and then we get

$$\theta = tan^{-1}\left(\frac{h}{z_c}\right)$$

then indicates the value of the tilt angle above the edges of the contact is 0° (h=0) (Figure 3) and equal to 45° when h=z_c and -45° when h=-z_c. Half the distance between the contours (± 45°) of the magnetic tilt angle gives the depth (Salem et al., 2007).

The important advantages of this method are its simplicity both in its theoretical derivation and

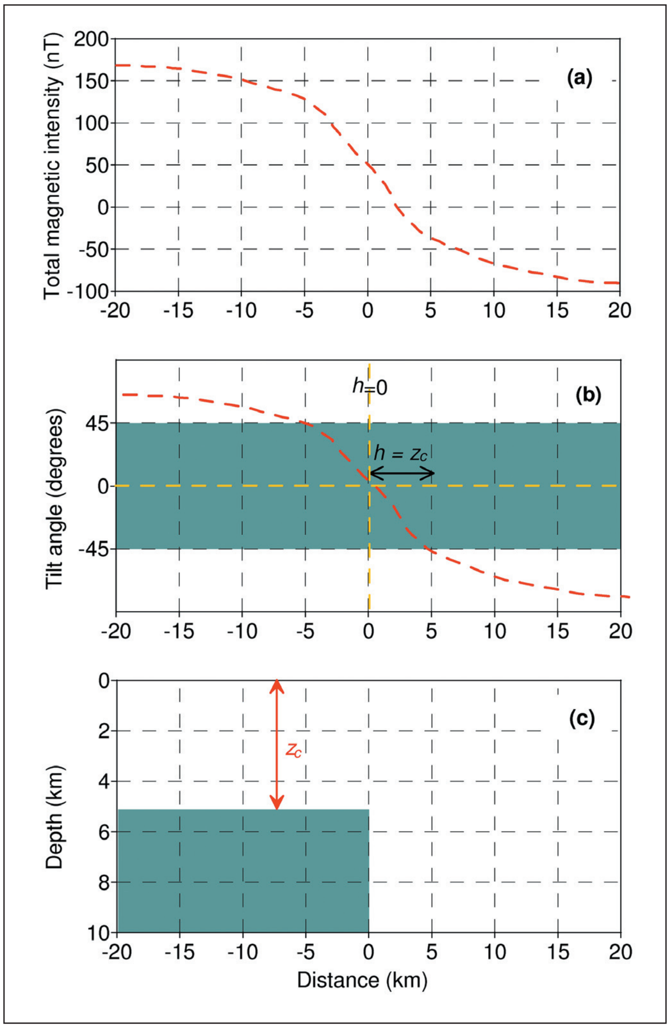

Figure 3- Vertical 2D contact model; a) Total magnetic anomaly, b) The tilt derivative over a vertical contact for reduced-to-pole data. Tilt values are restricted to within ± 90°. The point of coincidence of the part of the tilt derivative between ± 45° with the 0° gives the vertical contact, c) Model structure (Salem et al., 2007).

in its practice application and it provides both a qualitative and quantitative approach for the interpreter about location and depth, there is no need for parameters in calculations, and it is potentially less sensitive to noise comparing to the other methods using higher order derivatives.

THE GEOLOGY OF THE STUDY AREA

For the field application 1/100.000 scale KIRŞEHİR-İ31 map sheet, which covers an area of about 2250 km^2 over the Central Anatolian Metamorphic Massif, was selected (Figure 1).

Exploratory geological map of the sheet İ-31 was prepared by Dönmez et al. (2005) from the 1/500.000 scale Geological Map of Turkey (MTA, 2002) (Figure 4). Metamorphic rocks of Kırşehir Massif constitute the basement lithology of Kırşehir-İ31 sheet. Palaeozoic aged metamorphic rocks, affected from low-medium grade regional metamorphism, are generally composed of schist, gneiss and marbles. In the study area these metamorphic basement rocks are represented by marbles and recrystallized limestones (Seymen, 1982; Dönmez et al., 2005). Metamorphic basement rocks are covered by volcanic and sedimentary rocks of Late Cretaceous such as basic volcanites, volcanoclastic and pelagic deposits (Ketin, 1955; Ayan, 1963; Seymen, 1982; Kara and Dönmez, 1990). Volcanics are diabase dikes, basalts, spilitic basalts, alternating with pelagic limestone, mudstone and radiolarite at the bottom, and sandstone and siltstone having volcanic material on the top.

Metamorphic and volcanic rocks are cut by Late-Cretaceous-Paleocene aged plutonic rocks (Ayan, 1963; Ataman, 1972; Seymen, 1982). These plutonic rocks are mainly represented by granite, granodiorite, quartz diorite and syenite. In addition, volcanic and subvolcanic rocks (rhyolite, rhyodacite, trachite, etc) which are closely associated with these plutonic rocks were mapped together with plutonic rocks.

Early Tertiary aged marine sedimentary rocks unconformably overly all these units. These units, consist of a sequence of alternating red-colored terrestrial conglomerate, sandstone and mudstone at the bottom and shallow marine clastics and highly fossiliferous neritic limestones on the top deposited by Eocene transgression (Ketin, 1963; Birgili et al., 1975; Norman, 1972; Oktay, 1981; Kara, 1991; Dönmez et al., 2005). The marine units, which have a thickness of 500-800 m in the mapped area, are of Early-Middle Eocene age. With the regression which started in Late Eocene, the terrestrial-lacustrine units of Oligo-Miocene age, which widely outcrop in the north and east of the region, were deposited. These terrestrial units are represented by a sequence of alternating red-colored conglomerate, sandstone, mudstone at the bottom and by a sequence of alternating variegated lacustrine sandstone, claystone, limestone on the top. Evaporites (gypsum, anhydrite and salt) and ignimbritic tuffs are also observed commonly within these sequences (Pasquare, 1968; Birgili et al., 1975; Uygun et al., 1981; Kara and Dönmez, 1990; Dönmez et al., 2005). Overlying these terrestrial units, which have a thickness of around 100-1500 m, are Quaternary aged alluviums which outcrop in stream and valley bottoms.

FIELD APPLICATION

In this study regional gravity and aeromagnetic data were used. Magnetic data of the study area were taken from the aeromagnetic works of the General Directorate of Mineral Research and Exploration (MTA), conducted during the years of 1978-1989. In this work of MTA, which covered all over Turkey, the flights were carried out by taking into consideration the topography and geological trends. Flight altitude was tried to be maintained at around 625 meters.

The regional gravity data were first started to be taken in the year 1973 by MTA and completed in 1988 through a work lasted 15 years. The regional gravity data of Turkey were taken at intervals of approximately 3 and 5 km.

Tilt angle maps are very useful in that they facilitate the work of the interpreters. The field application was carried out making use of the model shown in figure 3 which shows the relationship between tilt angle and source depth. On the maps of gravity and magnetic tilt angle, the angles are shown in degrees (Figure 5c and 6c). The part between 45 contours is shown in yellow color. Half the vertical distance between these contours gives information about the depth of the body. The contours between 0° and +90°, shown

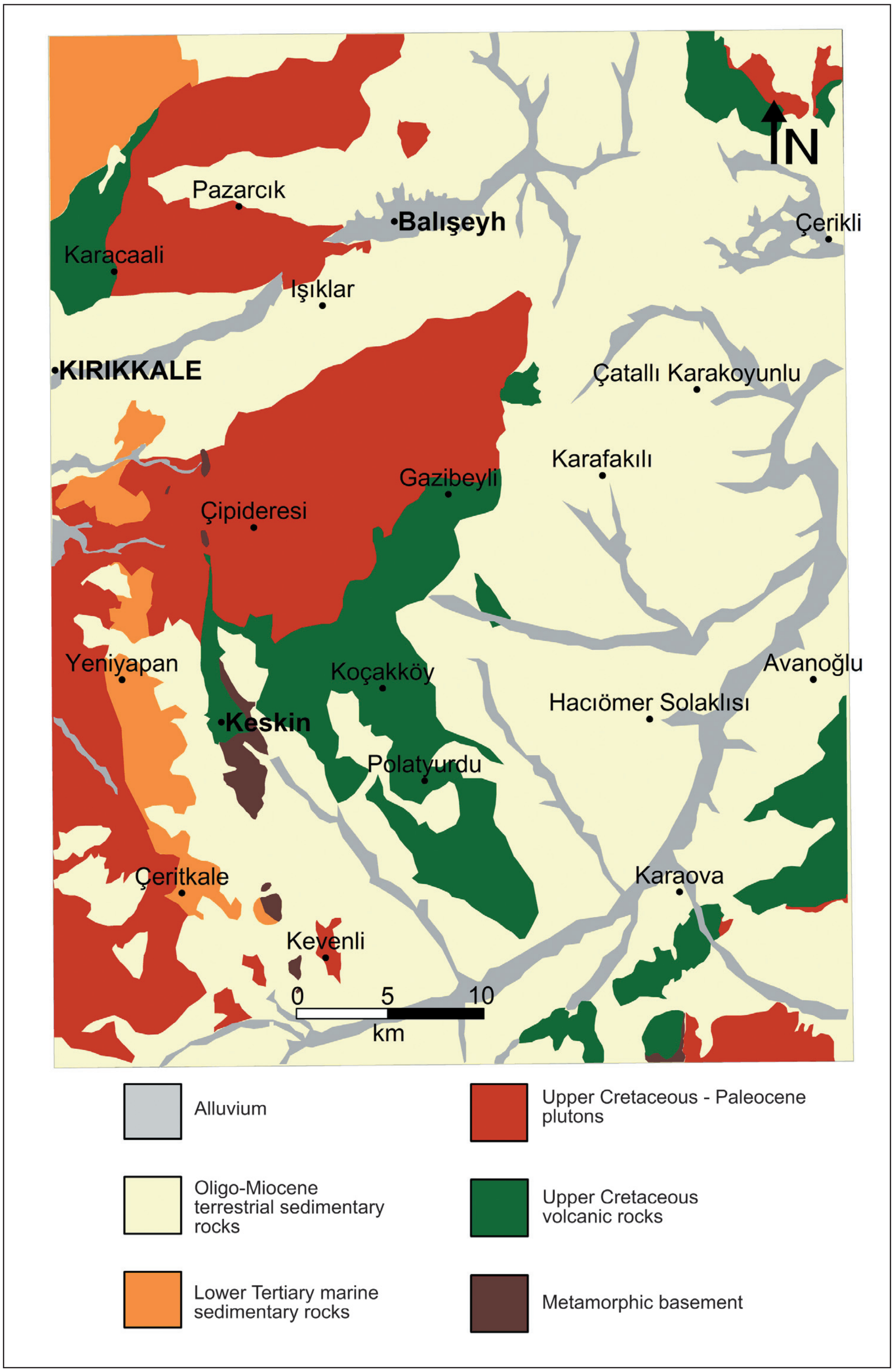

Figure 4- Geological map of 1/100000 scale Kırşehir İ-31 sheet (modified after Dönmez et al. 2005).

by blue-colored + symbol define the inside of the source and the interval between 0° and -90° defines the outside of the source. The 0° contour shown with red dashed lines determines vertical structural contacts (Figure 5c and 6c).

Reduction-to-the-pole operation was carried out on the aeromagnetic data in order to eliminate dipolar effect. In the application, the magnetic tilt angle map proved to be more complicated compared to that of the gravity tilt angle and made the interpretation considerably difficult. For that reason, in order to eliminate the noise resulting from short wave lengths, 5-km upward continuation was applied to the reduced-to-the-pole map (Figure 6b).

In figure 6c, the anomaly is bordered by 0° contour which follows the settlements of Çerikli, Çatallı Karakoyunlu, Gazibeyli, Koçakköy, Polatyurdu, Kevenli, Hacıömer Solaklısı and Avanoğlu. It is thought that the structure, which has high-amplitude magnetic anomaly and high susceptibility, was probably resulted from the volcanites underlying the thick terrestrial units (Figure 6b). It was observed that although Late Cretaceous aged volcanic rocks are present in the settlement area of Keskin, Koçakköy, and Polatyurdu on the geological map, magnetic anomaly amplitude was not high. The reason for that is the fact that the thicknesses of the volcanic rocks present here are low and the susceptibilities of the marbles within metamorphites belonging to Kırşehir Massif and Early Tertiary aged limestones are low. However, on the gravity Bouguer map it is seen that this anomaly continues in the region which comprises Koçakköy, Polatyurdu and Keskin settlements. And the reason for that is the fact that the volcanites are thin and the density of the metamorphic rocks which are situated at the basement and belong to Kırşehir Massif is higher than that of the volcanites. At the same time, the sporadic outcropping of the marbles and Early Tertiary aged limestones in the region gives rise to positive anomaly (Figure 4 and 5b).

On the other hand, the gravity Bouguer anomaly (Figure 5b) surrounded by Çatallı Karakoyunlu, Çipideresi, Yeniyapan, Kevenli and Karaova settlements is resulted from the fact that the density of the volcanic rocks is higher than that of the granites and terrestrial rocks. And the presence of magnetic anomaly in the same region corroborated the idea that terrestrial sediments are underlain by this volcanic unit.

It is thought that structural boundary differences on the maps of gravity and magnetic tilt angle are resulted from the reasons explained above (Figure 5c and 6c). It is observed that this large gravity and magnetic anomaly is not closed in the east of the sheet (Figure 5b and 6b). It was observed that there was continuation of the gravity Bouguer and magnetic anomalies seen on İ31 map sheet in the E-W extension, on İ32 and in part on İ33 map sheets (Akın and Çiftçi, 2010). For that reason, tilt angle work was applied also on İ32 map sheet and it was seen that the anomaly extended up to Çiçekdağ. Similarly, it is observed that the same lithological units outcrop at Çiçekdağ when the geologic maps of the region are examined (MTA, 2002).

It was determined that the magnetic anomaly observed in small areas to the north of the settlements of Karacaali and Pazarcık lying in the northwest of the field and also to the north of Çerikli settlement lying in the northeast of the field was also resulted from the volcanites (Figure 6b). In the same way, the gravity anomaly corroborates this (Figure 5b). The determined structural boundaries are observed on the tilt maps as well (Figure 5c and 6c). These structures were correlated with the volcanic rocks situated on the geologic map (Figure 4, 5a, 6a).

It is thought that the anomalies with low amplitude which are present to the south of the study area are resulted from the terrestrial unit with low density and low susceptibility and from the felsic granites (Figure 5b and 6b).

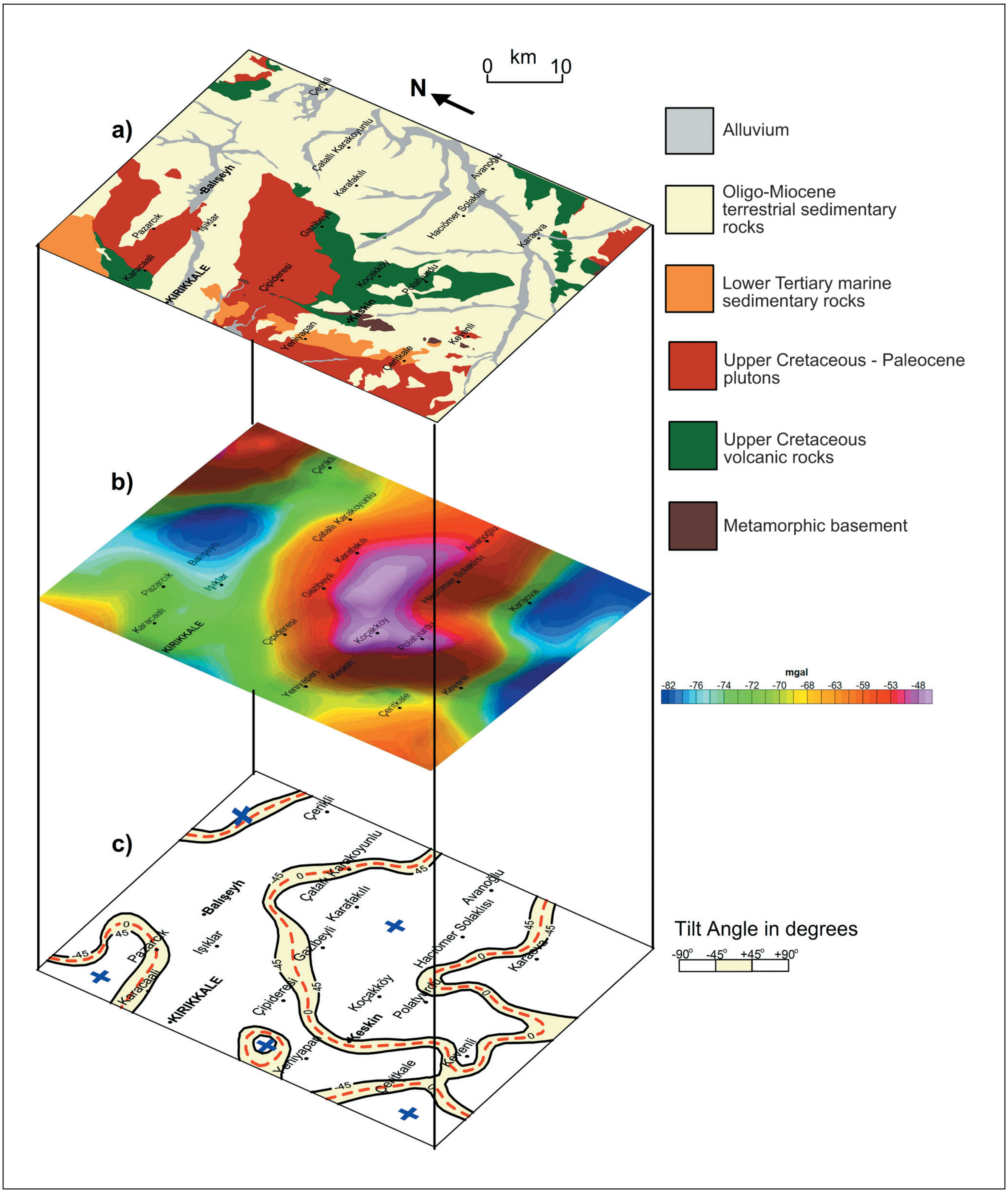

Figure 5- Comparison of study area; a) Geological map of Kırşehir İ-31 sheet b) Gravity Bouguer map c) Gravity tilt angle map.

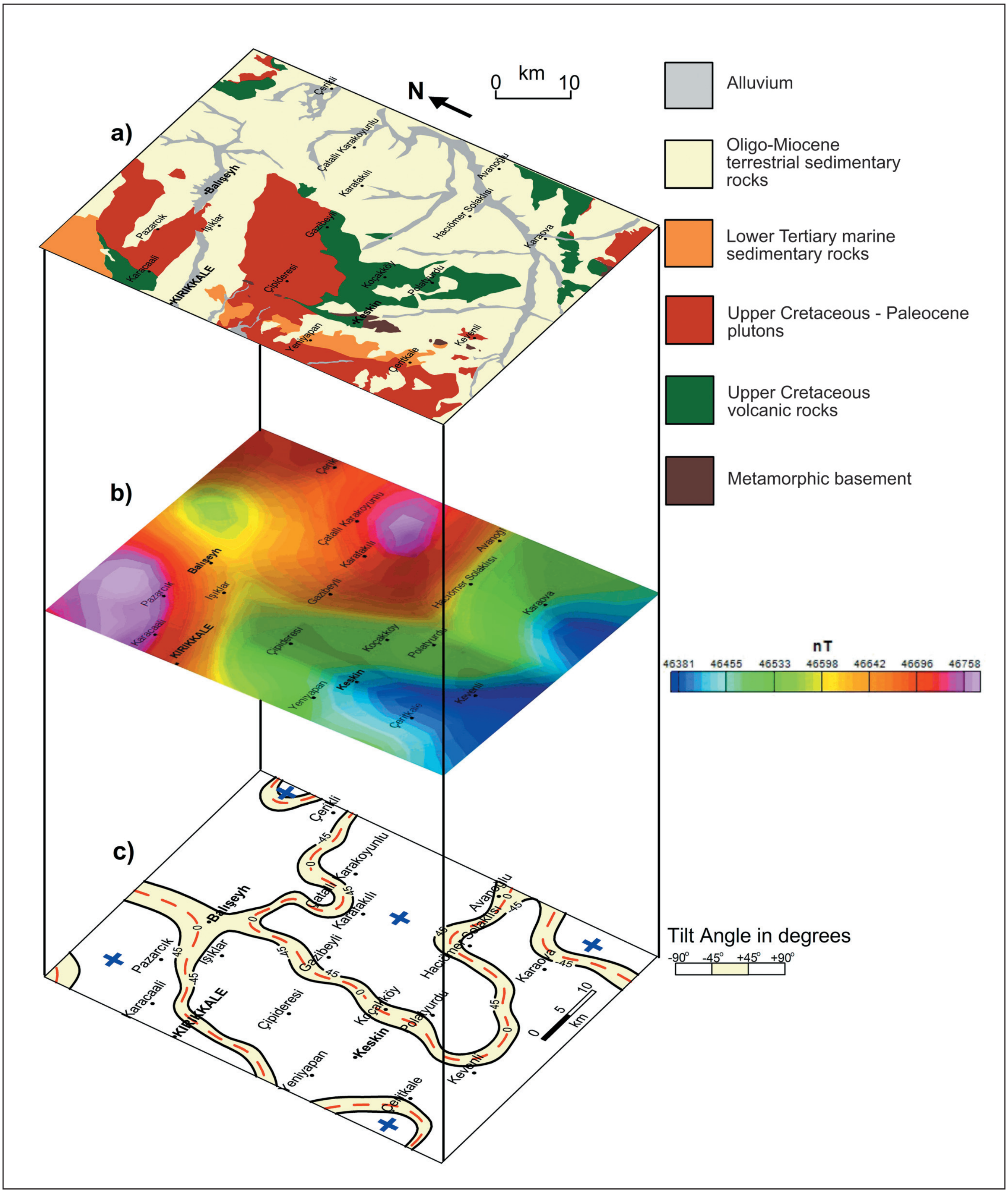

Figure 6- Comparison of study area; a) Geological map of Kırşehir İ-31 sheet b) Aeromagnetic Anomaly map (Reduced-to-the-pole, then a 5-km upward continuation applied), c) Magnetic tilt angle map.

Tilt angle contour orientations situated to the west of the study area were affected by the tectonic developments (the lithological difference between the units belonging to İzmir - Ankara Zone and Kırşehir Massif) which are present to the west of İ31 sheet (Figure 5c and 6c).

The fact that half the difference between the ±45° contours does not show much variation on the gravity and magnetic tilt angle maps expresses that structure depth does not show much variation in itself, either. Upper depths were determined between 0.5 and 2.0 km approximately.

RESULTS

The 'Tilt Angle' method, which is a fast and practical method in detecting vertical contacts, was applied to the regional gravity and aeromagnetic data of 1: 100.000 scale İ31 map sheet. Tilt angle maps which reveal the location of structural boundaries were obtained and they were correlated with the geology of the region.

By means of the work conducted here, information was obtained on the presence of Late Cretaceous aged volcanics buried under Tertiary aged sedimentary rocks in the field, their locations and average depths. Upper depths were determined between 0.5 and 2.0 km approximately.

This method brought a new point of view for the interpretation of geological problems and a practice practicability.

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