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HEAT FLOW OF THE KIRŞEHİR MASSIF AND GEOLOGICAL SOURCES OF THE RADIOGENIC HEAT PRODUCTION

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ABSTRACT.- It is not often easy to distinguish the components of the mantle originated heat flow and radiogenic heat generation from each other. Surface heat flow is composed of two components. The first is the radiogenic heat source and the second is the heat flow originated from the upper mantle and the lower crust. In this study, heat flow and the radiogenic heat production of the Kırşehir Massif and its geological sources were investigated. Curie point depths were calculated from aeromagnetic data. Geothermal gradient values were formed by considering the medium as homogenous and isotropic. The heat flow of the region was calculated using the heat transfer values of rock samples collected from field and it was determined that this value had ranged between 53 mWm^{-2} and 108 mWm^{-2}. Besides the radiogenic heat production of the study area has been calculated from the radiogenic heat production map of the region prepared by previously gathered airborne spectral gamma-ray data. As a result of the evaluation of heat flow and heat production maps together, it was calculated that 60-92% of the average heat flow values of the region are mantle and 8-38% are radiogenic sourced. The radiogenic heat production in the study area, generally showed high anomaly values in young granitoids as predicted.

Keywords: Kırşehir Massif, heat flow, radiogenic heat production, Curie depth.

INTRODUCTION

The heat on Earth's crust is formed by the constitution of mantle sourced heat and the heat derived by the degradation of radiogenic elements. The radiogenic sourced heat is formed by isotopes with short and long half lives on the Earth's crust. While radiogenic isotopes with short half life, (^{26}Al, ^{26}Cl and ^{60}Fe) were effective in producing the heat in the former stages of the Earth, isotopes with long half life (^{235}U, ^{238}U, ^{232}Th and ^{40}K) were effective in heat energies produced starting from the earlier stages of the Earth until today (Göktürkler, 2002).

According to Birch (1947), the radiogenic heat production on the upper part of the earth crust is associated with the distribution of thermal energy which radioactive elements had formed and with great tectonic processes. Turcotte and Schubert (1982) asserted that the radiogenic heat production is an important factor in the thermal structure of the continental crust. It was also explained in different studies that heat changes due to crustal processes such as metamorphism, magmatism and deformations are important in heat production (Bea et al, 2003; Andreoli et al, 2006, Sandiford and McLaren, 2006). Besides, Jaupart and Mareschal (2003) associated the studies of radiogenic heat production at surface with the heat flow at depths of the earth crust.

It will be useful firstly to introduce the regional geology and regional tectonic elements in order radiogenic heat production and other elements to be correctly interpreted in the study area.

REGIONAL GEOLOGY

The study area covers a significant portion of the Kırşehir Massif which takes place in the

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middle part of the Anatolian Plate (Figure 1). This massif defines the area which is bounded by the North Anatolian Fault Zone (NAFZ) at the north and the East Anatolian Fault Zone (EAFZ) at the east. In the area, several transform faults take place developed being associated with the main Neotectonic structures stated above (Figure 2). In the crustal thickness map of Turkey which has been produced by using the gravity data, the Kırşehir Massif has been cut by two profiles. The first and the second profiles are in north-south and east west directions, respectively. The crustal thickness of the Kırşehir Massif was calculated ranging in between 35 - 40 km along both profiles (Arslan et al., 2010).

In this study, the 1/500.000 scale Kayseri sheet which had been published by MTA (General Directorate of Mineral Research and Exploration) (2002) was used as the geological base map. This map was re-prepared by being simplified depending on the purpose of the study and units were presented according to their origins (Figure 3). The basement of the study area is generally composed of Cambrian-Ordovician aged metamorphic schists, Precambrian / Palaeozoic aged gneiss, schist, amphibolite and similar metamorphic rocks and of Permian aged marbles (Figure 3). In the region, plutonic activities in various composites have been formed in Upper Cretaceous - Eocene period and these are generally represented by the Upper Cretaceous - Paleocene aged granitoids and syenites. The Upper Cretaceous - Paleocene aged volcanites have taken their recent positions in the region as the last stage products of this magmatic province. Ophiolitic complex associated with the forming of the İzmir - Ankara - Erzincan Suture zone and various products of it have emplaced in the region within the same period (Figure 3).

STRATIGRAPHY

Metamorphic rocks take place at the basement of the study area (Figure 3). Opholitic groups have tectonically overlaid these basement rocks. Magmatic intrusive rocks and their volcanic associates have taken place within the region by cutting the basement rocks and the ophiolitic groups. All these metamorphic and magmatic series have been covered by volcano-sedimentary and sedimentary series starting from Eocene with volcanics and then continued with clastics (Figure 4).

In compliance with the purpose of the study, rock assemblages within this area were briefly introduced below.

Metamorphic basement rocks

Metamorphic rocks consisting of the basement of the study area are represented by several formations having various mineralogical compositions. Cambrian - Ordovician aged rocks outcrop in NE of the study area and NW parts of Nevşehir. The oldest unit distinguished at the Palaeozoic basement was named as Gümüşler formation by Göncüoğlu (1977) (Figure 4). This formation mainly bearing of lithologies such as gneiss, sillimanite bearing gneiss, marble, calcschist, amphibolite schist, micaschist which extensively crop out in the east and northeast (Figure 3).

Gümüşler formation at the basement is conformably overlain by Kaleboynu formation (Göncüoğlu, 1981) which consists of lithologies such as gneiss with biotite and garnet, amphibole schist, marble and muscovite schist and is Precambrian - Palaeozoic in age. This formation constitutes the main lithologies cropping out in the study area and was divided into three units. These are, from bottom to top, Sarıkavak Unit (gneiss with biotite, marble and amphibole schist), Marble unit (marble and calcschist) and Muscovite schist unit (quartz, muscovite schist, calc schist and marble).

The deposit on the uppermost layer of the metamorphic basement rocks was named as Bozçaldağ formation (Seymen, 1981*a*). It gene-

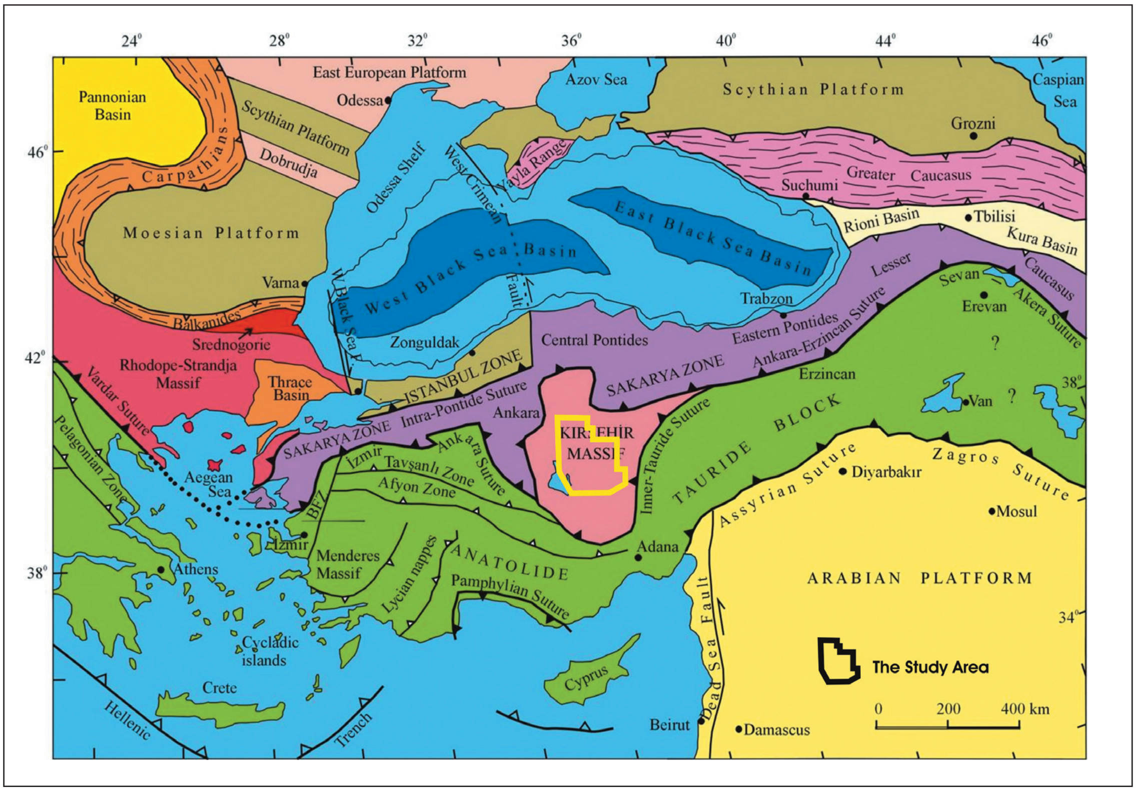

Figure 1- The overall tectonic view of the study area (area drawn in yellow line) (modified from Okay and Tüysüz, 1999).

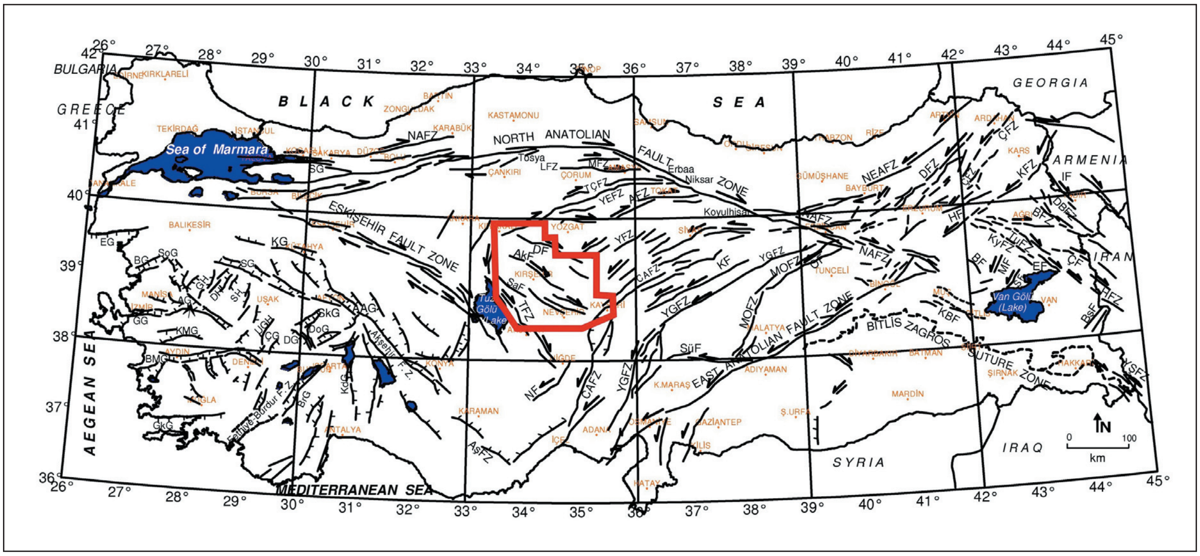

Figure 2- Neotectonic discontinuities of Turkey prepared by Bozkurt (2001) by combining the maps of Bozkurt, 2000; Yılmaz et al, 2000; Seyitoğlu 1997; Şaroğlu et al, 1992; Koçyiğit, 2000; Koçyiğit et al, 2000; Bingöl, 1989; Koçyiğit and Erol, 2001; Bozkurt and Koçyiğit, 1996 and Dirik and Göncüoğlu, 1996). Area drawn in red shows the location of the study area (modified from Akın and Çiftçi, 2011).

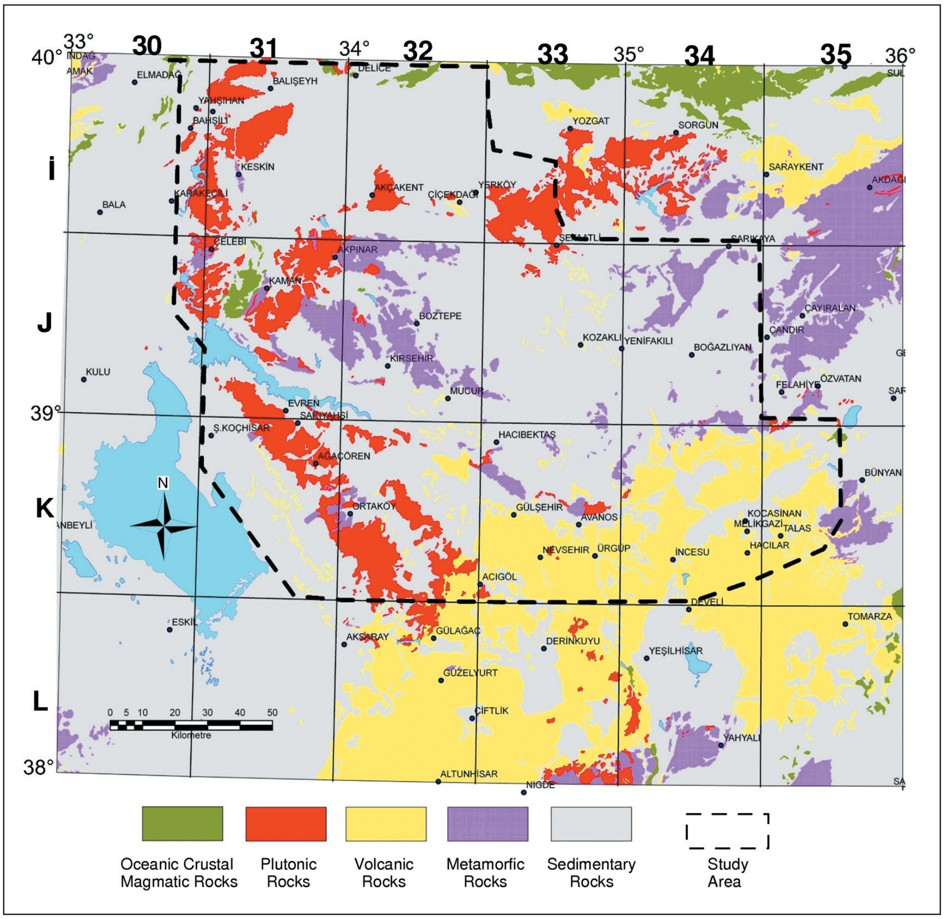

Figure 3- Geological map of the study area (simplified from 1/500 000 scale Kayseri Sheet, MTA, 2002).

rally consists of marble and is Permian in age. This formation was distinguished as Aşıgediği formation by Göncüoğlu (1977) and as Bozçaldağ marbles by Kara (1977).

This formation shows extension in middle and northeastern parts of the study area. Significant skarn zones were formed sporadically in places where it was cut by magmatic rocks in NW of Kırşehir (Kara, 1977).

Ophiolitic complex

Two different ophiolitic series crop out in NW and NE of the study area. Ophiolites cropping out in north of Yozgat are known as ophiolites of İzmir - Ankara - Erzincan Zone. Ophiolites remaining within portion of the study area of this zone were nomenclatured as Artova Ophiolitic Complex (Özcan et al., 1980) and mainly consist of undistinguished slices and blocks of basic, ultrabasic, volcanic, metamorphic and of sedimentary rocks (Figure 3 and 4).

However, ophiolitic series dispersing at NW of the study area was nomenclatured as Çiçekdağ formation (Kara and Dönmez, 1990) and is generally in a view of volcano sedimentary group. This formation is also equivalent to groups

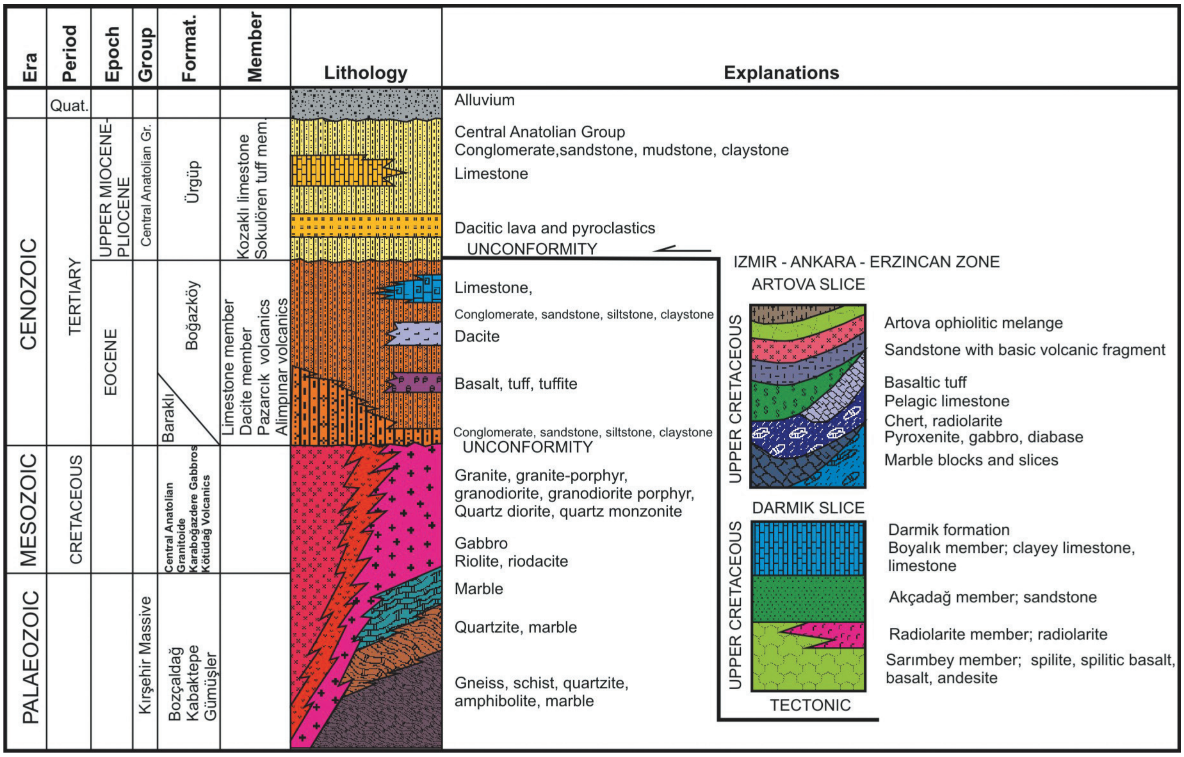

Figure 4- Generalized tectono - stratigraphic columnar section of the study area (simplified from Akçay et al., 2008).

defined as serpentine and radiolarites (Baykal, 1943), as Upper Cretaceous submarine volcanic series / ophiolitic series (Ketin, 1955, 1963), as Ankara melange (Bailey, McCallien, 1950), as Yahşihan formation (Norman, 1972), as Ankara Complex (Seymen, 1982) and as Kasımağa formation (Bilgin et al., 1982) (Figure 3 and 4). Black - dark green gabbro and micro gabbros observed within the basement of this formation were defined as Karaboğazdere gabbro unit by Bilgin et al. (1986). This unit is the equivalent of basic intrusives (Ketin, 1955; Ayan, 1963), Karakaya Ultramafics (Seymen, 1982) and Ortaköy granitoid (Atabey et al., 1987) (Figure 4).

The Central Anatolian granitoids

Granitoids exposing in the study area were discussed under this subsection, although their compositions and time of emplacements are different (Dönmez et al., 2005*a*). Granitoids belonging to this group have been investigated under various names such as Baranadağ massif (Ayan, 1963), Cefalıkdağı granodiorite (Ataman, 1972), Karacadağ pluton (Norman, 1972), Üçkapılı granodiorite (Göncüoğlu, 1977), Baranadağ pluton (Seymen, 1982), Ortaköy granitoid (Atabey et al., 1987) in previous studies.

The Central Anatolian granitoids, starting from the NW of the study area extend as an assemblage approximately in N - S trend around Kırıkkale, as an assemblage in NE - SW trend around Yozgat and as an assemblage trending in NW - SE at the east of Tuz Lake. Besides, another assemblage is observed between Kırşehir and Kırıkkale (around Kaman) trending in NE - SW (Figure 3) too.

These units were mapped as assemblages of four compositional groups emplaced in different time intervals in the 1: 500 000 scale geological map of Turkey. All Late Cretaceous - Paleocene aged granitoids will be introduced under two categories in compliance with the regional approach of this study (Figure 3).

Granitoids.- Granitoids outcropping to the east of Aksaray in the study area were nomenclatured as Ortaköy granitoid (Atabey, 1989). The same granitoids were defined as Ekecikdağ granitoids by Türeli et al. (1993). While this granitoid includes both mafic and felsic units, the members of deep and shallow emplacements are accommodated in it as well. Mainly; gabbro, banded gabbro, diorite, tonalite, granite, granodiorite, porphyry diorite, monzonite, syenite, monzodiorite, leucogranite and porphyry granite units were distinguished (Atabey, 1989). This rock assemblage is equivalent of Baranadağ pluton (Seymen, 1981) in literature. The intrusion and cooling age of this pluton was given as 54 ma by Ayan (1963), 74 ma by Ataman (1972) and as 95 ma by Göncüoğlu (1982, 1986). However; the age of this pluton is Paleocene according to Seymen (1981*b*).

Granitoids exposing to the east and southeast of Kırıkkale cut Bozçaldağ and Santonian aged Çiçekdağ Formations of the Kırşehir Massif with a hot contact (Dönmez et al., 2005*b*).

Granitoidic group at south of Yozgat is composed of shallow seated pluton and stocks of various stages and phases and vein rocks which developed in their outer zones (Akçay et al., 2007).

Syenites.- Magmatic rocks spreading towards northern parts of 1/100.000 scale Kırşehir J31 and J32 sheets and successively associating with Central Anatolian granitoids were nomenclatured as Buzlukdağ syenite in the region (Kara and Dönmez, 1990). This assemblage is equivalent of Buzlukdağ pluton and was defined by Seymen (1982).

Syenites which crop out generally between Çelebiuşağı and Himmetuşağı settlements to the NE of İ33 sheet is composed of micro syenite, trachyte, quartz syenite, quartz micro syenite, quartz trachyte and alkali syenite type of lithologies.

These rocks are transitional with the Central Anatolian granitoids (Dönmez et al., 2005*b*). However, it was stated that while granitoids are cut by phonolites, syenites are cut by porphyry granodiorites respectively (Kara and Dönmez, 1990).

Volcanic series

A volcanic series crops out in E- W direction along the southern boundary of İzmir - Ankara - Erzincan Zone towards northern parts of the study area (Figure 3). This Late Cretaceous aged volcanic series cropping out in the region was defined as Darmik formation and is characterized by agglomerate, tuff, sandstone, pelagic limestone, basaltic andesitic pillow lava, radiolarite, and are cut by andesitic, basaltic and porphyry dikes (Akçay et al., 2008) (Figure 4).

Lithological assemblages contemporaneous with the deposit between Kırşehir and Kırıkkale mentioned above was named as Kötüdağ volcanite (Seymen, 1982) and mainly consist of vein and surface rocks composed of rhyolite, rhyodacite, dacite and latite. These are the last stage volcanic deposits of the Central Anatolian granitoids and were generally developed around the outer zones of these granitoids.

Sedimentary deposits

Although clastic and carbonaceous deposits widely spreading in the study area have been mapped in details with different purposes and several deposits have been distinguished, all these terrigenous and lacustrine deposits in this study will be presented under the name of "Central Anatolian Group" (Akçay et al., 2008).

Middle Miocene - Pliocene aged continental deposits which show a wide distribution in the Central Anatolian Region were formed by reddish brown, none or less markedly bedded conglomerate, sandstone, mudstone, gypsum, anhydrite and by intercalations of limestone and ignimbrite. These groups were collected under the name of "Central Anatolian Group" and mapped by Akçay et al., (2008) (Figure 3, 4). It was stated in this study that, this deposit was equivalent of a part of the Kızılırmak formation defined by Birgili et al. (1975). The lower contact of the deposit shown in figure 4 is unconformable. Sokulören Tuff unit (Akçay et al., 2008) which is composed of dacitic lava and pyroclastics takes place in the lower sections of the sequence namely the Ürgüp formation (Pasquare, 1968) which is generally composed of conglomerate, sandstone, mudstone and claystone intercalations. However, at mid sections of the sequence, Kozaklı limestone unit takes place (Kara and Dönmez, 1990) which shows laterally transitional contact relationships with the surrounding units (Figure 4). Since the radiometric age taken from the oldest ignimbrites exposing around Ürgüp is 11.2 ± 2.5 ma (Temel, 1992), the age of this deposit is accepted as Late Miocene (Akçay et al., 2008).

All deposits in the study area are covered by Quaternary clastic deposits with an angular unconformity.

HEAT FLOW

PREVIOUS STUDIES AND OUTLINE

Surface heat flow is the heat value transferred from a unit area at a unit time from depths of the ground to outer side and its unit is mWm^2. Heat flow studies in Turkey have been made in regional scale or as overall Turkey so far (Ericson, 1970; Jongsma, 1974; Fytikas, 1980; Tezcan and Turgay, 1989; İlkışık, 1992 and 1995; Yemen, 1999; Göktürkler et al., 2003; Bal, 2004; Akın and Duru, 2006; Akın et al., 2006; Karlı et al., 2006). In these investigations, it was stated that heat flow values were observed that these had reached high values in corrections made due to rapid sedimentation although these were low in Mediterranean and Black Sea (Ericson, 1970). Heat flow studies are also available in Aegean Sea (Jongsma, 1974). According to the heat flow estimations in Aegean Sea, three high heat flow regions were determined extending along tectonic structures. The first is the region with high heat flow reaching out Bodrum Karaada vicinity through Astipalia, Kavaro islands along Palegonia - Parnos Zone which is located in inner part of Hellenic island arc (Figure 1) and it presents values exceeding 120 mW/m^2 sporadically. The second is the region exceeding 100 mW/m^2 located in Central Aegean, on the western end of the İzmir - Ankara zone (Figure 1). The last region is the high heat flow anomaly belt observed along Macedonia, northern Aegean islands and shores of Biga and Gelibolu peninsula (Fytikas, 1980).

Tezcan and Turgay (1989) prepared heat distribution map for 1000 m. depth selecting the average heat transmission coefficient as λ=2.1 (W/m°C) for overall Turkey. İlkışık (1992, 1995) has carried out heat flow studies of Turkey by silica heat method. The investigator has performed regional heat flow studies in west Anatolia using silica geothermometer in thermal sources and proposed average heat flow values as 107±45 mW/m^2.

Yemen (1999), assessed the heat flow distribution values of Aegean Region using geothermal gradient values in wells. However, Göktürkler et al. (2003) modelled crustal temperatures in the west Anatolia by two dimensional profiles and measured the heat distribution of grabens which are full of sediments in the upper crust and in lower parts of the crust. Bal (2004) carried out a study towards the determination of heat flow values by using aeromagnetic data of Aydın and İzmir vicinities and the investigation of the heat flow distribution. One of the two studies in which heat flow map of Turkey had been prepared by

Akın and Duru (2006) and the other belongs to Karlı et al. (2006). Akın and Duru (2006) carried out their investigations using Curie point depths calculated from aeromagnetic data, however, Karlı et al. (2006) performed their studies measuring geothermal gradient in shallow deep cold water wells.

DATABASE AND METHOD

MTA started to carry out aeromagnetic studies in 1978 in order to explore underground resources and ended in 1989. During 11 years period, the regional aeromagnetic map of Turkey has been generated performing 460 000 km flight above 2 000 feet from ground. Flight lines have been selected as 1 - 5 km intervals. IGRF 1985 magnetic correction has been applied in estimations. Within this period, total of 813 639 km^2 has been surveyed as sea, lake and land. In accordance with boundary conventions, boundaries of Syria, Iran and Iraq have been approached not more than 5 km and 15 km distance have been preserved with the former Soviet Union, Greece and Bulgarian boundaries.

Magnetic anomaly map which was prepared by aeromagnetic data of the study area and its vicinity is shown in figure 5. When looking at this map, it is seen that the highest magnetic anomaly values are formed along Akçakent - Yerköy - Çiçekdağ line, towards the east of Keskin. A weak magnetic anomaly belt directing in SW - NE could also be defined in the same Figure along the Nevşehir - Keskin line. Anomaly belts on this map were discussed in detail in studies of Akın and Çiftçi (2010).

By using the database shown above, the Curie point depth map was obtained (Akın and Çiftçi, 2010). Geosoft Oasis package software was used in producing maps. Curie point is the depth at which the magnetite mineral loses its magnetic property under the temperature of 580°C and gains paramagnetic property. Window in 128 x 128 km dimensions was used at Curie point measurement. Windows were positioned as shifting 32 km side by side towards east and two dimensional power spectrum of each window was calculated. Then values obtained were assigned to midpoint of the window. In doing so, the Curie point depth map was obtained applying the method which Tanaka et al. (1999) had revealed who developed the spectral analysis technique which Spector and Grant ((1970) and Okubo et al. (1985) had applied (Figure 6). Curie points in the study area were calculated as 11 km at the shallowest point and 15 km at the deepest point. The effective anomaly in figure 6 is in E - W direction and represents shallow depths. Curie depths of the northern part of the study area seem approximately 2 km shallower compared to southern part.

Surface heat flow is affected from astenosphere and lithosphere. Regional heat flow values obtained from surface provide significant contributions in assessing the geological structure of the region. In this study, geothermal gradient data was obtained using Curie point depth values in Figure 6. However; heat transmission coefficients of 32 rocks representing the study area were calculated by Karlı et al. (2006) in laboratory using QTM (Quick Thermal Measurement) device. These values were then used in calculating the heat flow (K). The heat flow map of the region was produced using the formula given in equation 1 (Figure 7).

$$q = K\,(\partial T/\partial z) \qquad (1)$$

where;

K: thermal conductivity,

q: surface heat flow,

$(\partial T/\partial z)$: vertical heat gradient.

Heat transfer coefficients of rocks in the region (as average value) were estimated as 2.5 W/m°C for plutonic rocks, 2.75 W/m°C for meta-

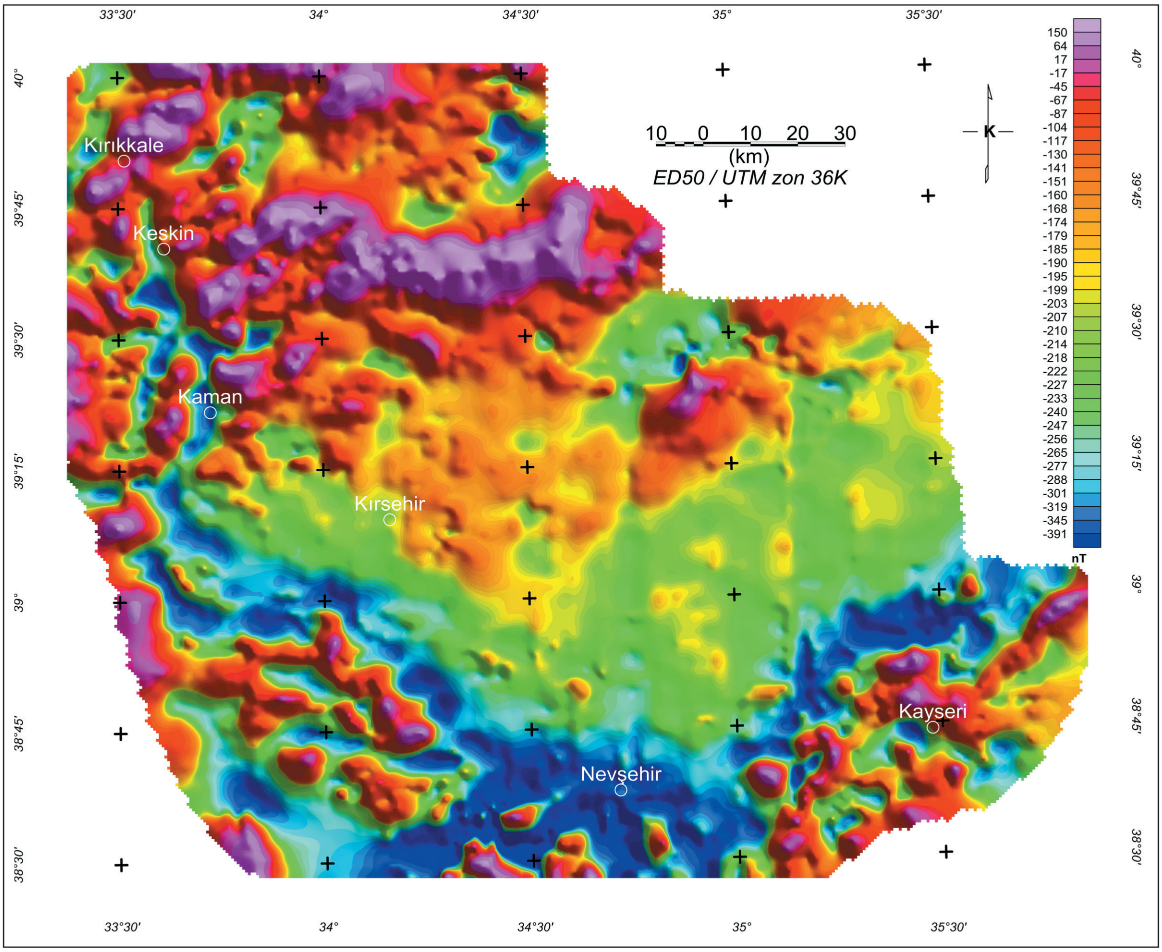

Figure 5- Aeromagnetic anomaly map of Kırşehir vicinity.

morphic rocks, 1.87 W/m°C for volcanic rocks and as 2.06 W/m°C for sedimentary rocks.

When looking at the heat flow map of the region, it was seen that heat flow values vary in between 50 mW/m^2 and 110 mW/m^2 (Figure 7). The average heat flow of the region was estimated as 72 mWm^2. This value is again compatible with the average heat flow value of the 1/500.000 scaled Kayseri sheet on the heat flow map of Turkey which was produced by using aeromagnetic data (Akın and Duru, 2006). The anomaly possessing the high heat flow on heat flow map (Figure 7) is approximately in north - south direction. However; the region that have low heat flow was located at northwest of Kayseri and southwest of Nevşehir.

RADIOACTIVE HEAT PRODUCTION

THEORY AND LITERATURE

"Radiogenic heat" forms as a result of the natural decay of radioactive elements such as uranium, thorium and potassium on Earth's crust. As a result of the decay of radioactive elements, α and β particles release, and electromagnetic wave propagation occurs. As a result of both the absorption of electromagnetic waves by other atom in medium and the collision of other atoms

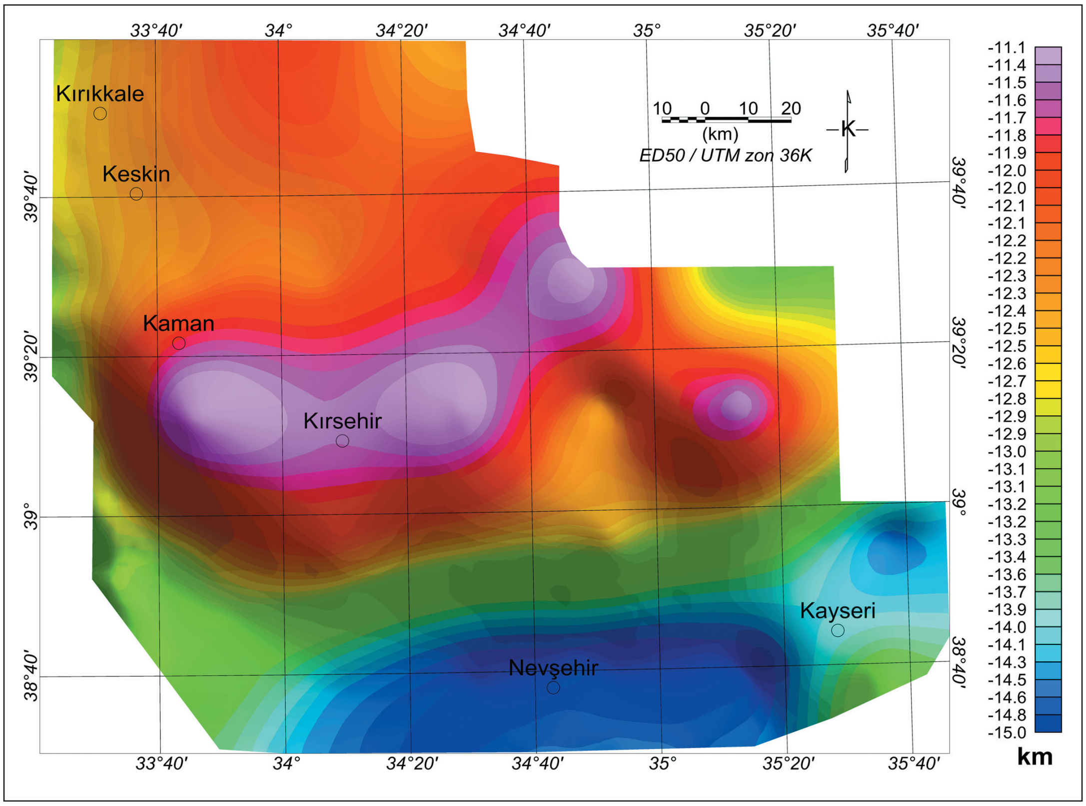

Figure 6- Curie point depth map of the study area (from Akın and Çiftçi, 2010).

with α and β particles, an increasing occurs in the kinetic energy of these atoms. Thus, the average kinetic energy of the medium, that is; the temperature increases (Göktürkler, 2002). The energy released from the radiogenic heat on the upper crust and this energy is added to the heat flow of the lithosphere and causes the rising of the heat flow value. Radiogenic heat originating from crust forms the 50 - 70% of the total heat generally radiated from the uppermost portion of the continental basement (Rudnick and Fountain, 1995; Waples, 2001). According to Mc. Lennan and Taylor (1996), the radiogenic heat value of the earth crust remains between 21 mW/m^2 and 34 mW/m^2.

DATABASE AND METHOD

The database of this study is the radioactive data collected from the aerial gamma ray spectrometer research which was conducted in Kayseri - Kırşehir - Yozgat and around Nevşehir in years 1987- 1988. In that research a total area of 25 000 km^2 has been surveyed. The survey has been carried out by Cessna 402B type aircraft belonging to the General Directorate of Mineral Research and Exploration (MTA) using 33.5 liter in volume crystal spectrometer. Instrumental support of the project was supplied by International Atomic Energy Agency (IAEA). This research has provided data to the project of the Central Anatolian uranium survey (Aydın, 1990).

Radiogenic heat production on crust is denoted by symbol A and its unit is $\mu W/m^3$. Rybach empirical formula was used in calculating the radiogenic heat production (Rybach and Buntebarth, 1982). It is necessary to know the uranium, thorium and potassium concentrations

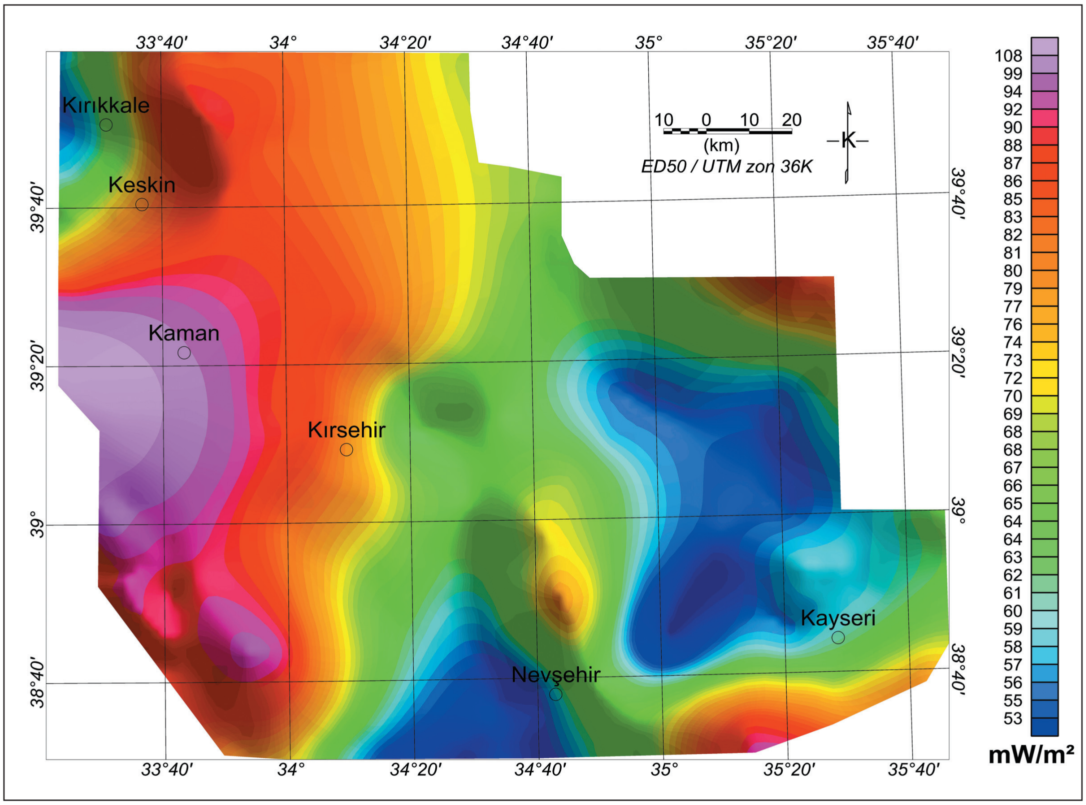

Figure 7- The heat flow map of the study area.

and density values of rocks in the equation given below.

$$A(\mu W/m^3) = 0.1325\,\rho\,(0.718\,C_U + 0.193\,C_{Th} + 0.262\,C_K) \tag{2}$$

where;

C_U: Uranium concentration (in ppm),

C_{Th}: Thorium concentration (in ppm),

C_K: Potassium concentration (in wt %)

ρ: density (g/cm^3).

Density values (ρ) of rocks in this study were taken as a constant but apparent densities were obtained for each cell from Bouguer gravity map. Apparent density values range in between 2.27 g/cm^3 and 2.64 g/cm^3. Later on, equation (2) was used to obtain the radiogenic heat production map (Figure 8). Radiogenic heat value shows variation between 0.62 μW/m^3 and 5.68 μW/m^3.

THE RELATIONSHIP BETWEEN THE HEAT FLOW AND RADIOACTIVE HEAT PRODUCTION

There is a linear relationship between the heat flow and the radiogenic heat production (Birch et al., 1968).

$$q = q_o + Ab \tag{3}$$

where;

q : surface heat flow,
q_o : reduced heat flow,
A : radiogenic heat flow,
b : slope of the line.

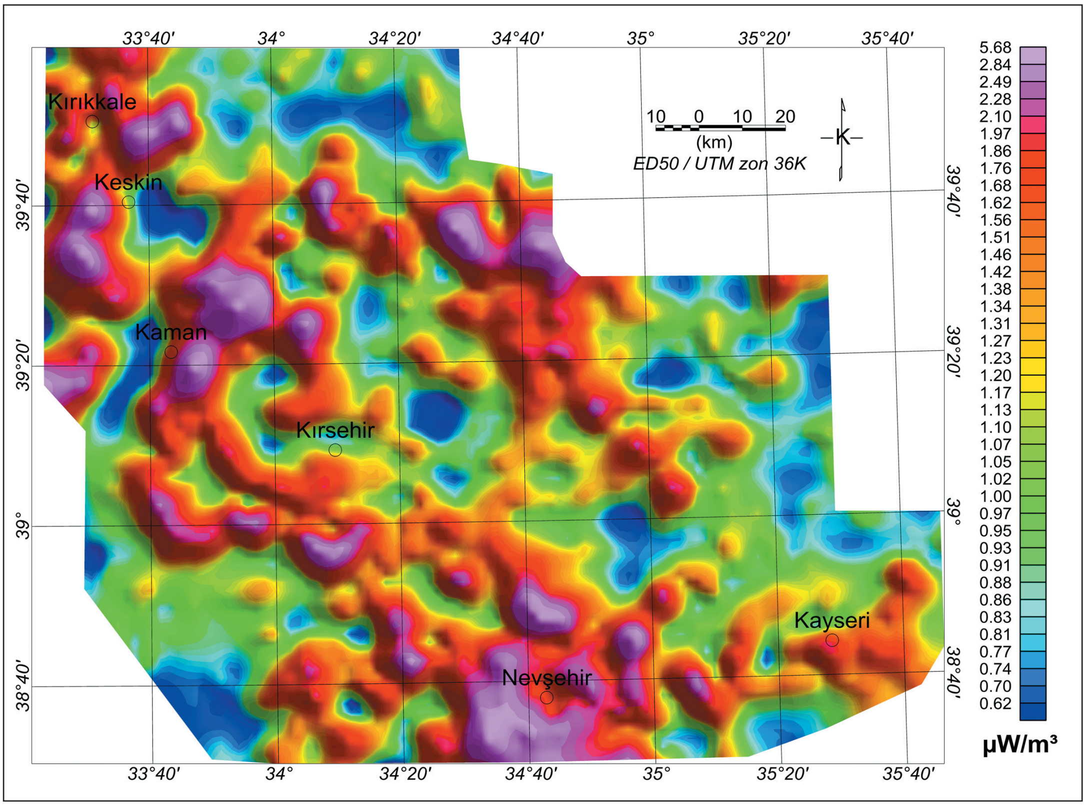

Figure 8- Heat production map of the study area originated from U, Th and K radiogenic elements.

b is the characteristic depth at which the radiogenic heat flow equals zero and q_0 is the mantle source heat flow at which the radiogenic heat production on crust equals zero. This value is represented by the equation (4) which was produced by using equation (3) (Blackwell, 1971).

$$q_0 = q - Ab \tag{4}$$

The ratio among heat amounts revealed by the mantle source heat flow and the radiogenic source heat production were calculated and its graph was formed (as percentage) (Figure 9).

The relationship coefficient in this graph is low as data scattering is randomly distributed. Therefore; b value was accepted as 10 km instead of 8.27 and the percentage amount map was obtained from the mantle source heat flow in figure 10.

Mantle source heat flow has shown variations between minimum 60% and maximum 92% in the study area (Figure 10). Thus; the heat flow amount originating from the decay of radiogenic elements (U, Th and K) in this area is between minimum 8% and maximum 40%. The region where the mantle source heat flow is the lowest in percentage are areas where Quaternary aged pyroclastic and basalts spread out in and around Nevşehir (Figure 3, 4 and 10). The heat flow of the region of which its coordinates are 33°40' - 34°30' in longitude and to the north of 39°40' in latitude is mantle source as in percentage of 85 - 92%. This anomaly most probably occurs due to magmatic rocks originating from the ocean

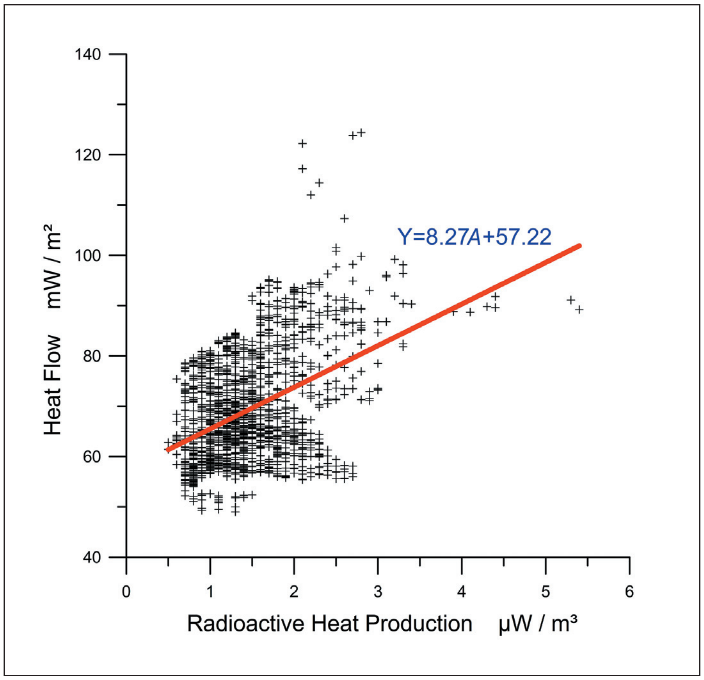

Figure 9- The relationship between the heat flow and the radioactive heat production.

bottom which is considered that it continues beneath the sedimentary rocks in the region and shows small outcrops sporadically (Akın et al, 2011). Thus; it is known that q_o parameter (reduced mantle source heat flow) in Birch - Lachrenburg Equation has high values in active regions in terms of tectonism and magmatism. With this respect, findings might give significant clues related to the tectono-magmatic activity in the region. The region where q_o component is high (north of Kaman) is equivalent to the area where alkali syenites occur which its formation is considered due to the contemporary tensional tectonic regime. When aforesaid data were totally assessed, we consider that high q_o component in the related region might indicate a magmatic mass which its cooling process still continues.

DISCUSSION

The heat flow and radiogenic heat production reveals thermal behavior types of areas. Generally data group obtained from well logs are used in such studies. However, in this study, grid data were fully used in estimations in order to reveal the heat regime of the Kırşehir massif located in Central Anatolia. The reason is that all data were not present at the same observation points. In order to ease calculations in data analyses in the study area, field data were used converting them into grid data. It can be said that grid intervals of aeromagnetic, aerial spectral gamma ray and on land regional gravity data were compatible with the purpose of this study and consisted of sufficiently small intervals and frequent data.

The density value in equation (2) used in calculating the radiogenic heat flow was obtained from apparent densities coming from Bouguer gravity map. Instead of using only one average density value for the whole area, density values for each grid areas were formed to increase analysis sensitivity in lateral sense. In doing so,

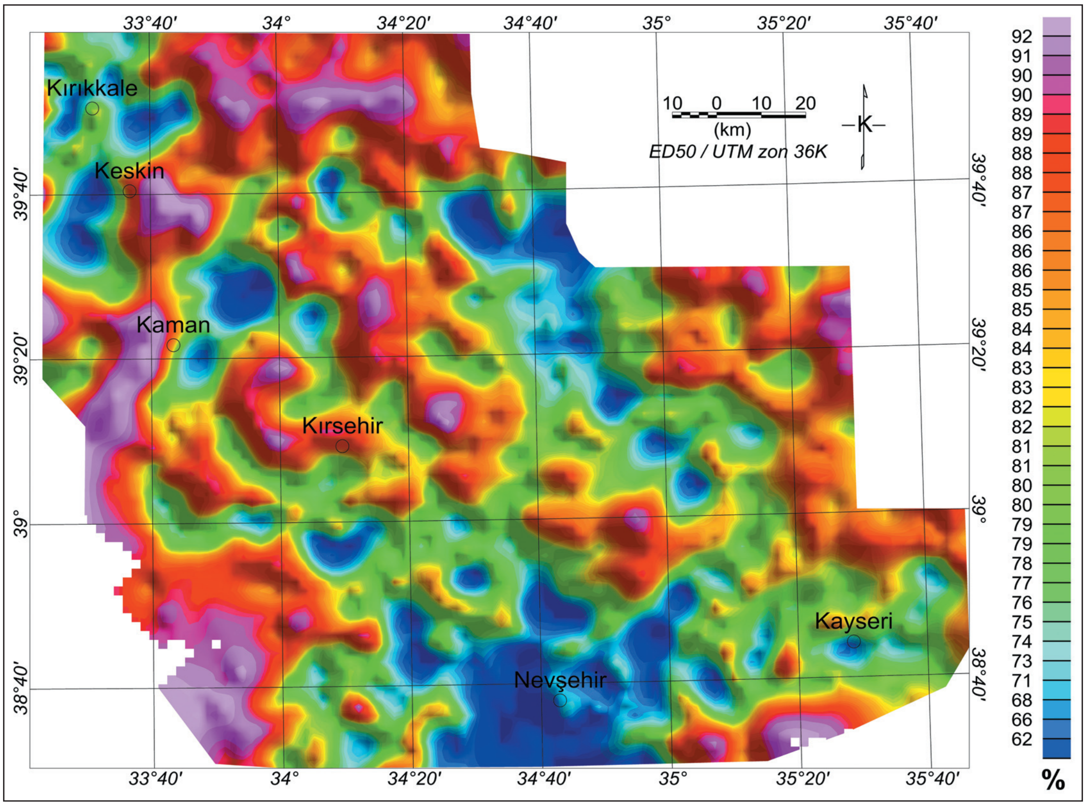

Figure 10- The percentage amount of the mantle source heat flow of the study area.

rock assemblages were represented in more detail.

Rock heat transfer in equation (1) which was used for obtaining the heat flow map or the grid file in which thermal conductivity coefficient had been used was generated by 32 data. Undoubtedly; more field data will give better results.

As also seen in figure 11a which shows the relationship between rock assemblages and the heat flow, high standard deviation values indicate that margin of error in calculations is high. In the study, the b coefficient in which the radiogenic layer depth has been used in equation (4) were calculated as 8.27 km using the linear equation Y=8.27A + 57.22 (Figure 9). Nevertheless; as data scattering in this graph is excessive, 10 km depth value which is much accepted in world literatures was assigned as b coefficient and was used in calculations. The mantle source heat flow in map produced by using this value (Figure 10) was estimated as 60% in minimum and 92% in maximum.

Bar graphs in figure 11 were produced using 311 data from volcanic rocks, 415 data from sedimentary rocks, 194 data from plutonic rocks and 111 data from metamorphic rocks which were located in the study area. Numerical values given in parentheses in each bar, state the standard deviation values of average values belonging to that rock group.

Standard deviation values of heat flow data in figure 11a were high and values showed variations in between 7.2 and 8.7. It was seen that the magnitudes of heat flow bars among rock groups in this diagram did not show much variation. Only plutonic rocks showed the most variation in the heat flow.

Radiogenic heat production in plutonic rocks in figure 11b is over the average 2 μW/m². Whereas; the average radiogenic heat productions in metamorphic and sedimentary rocks are rather low.

Figures 11c, 11d and 11e show average ratios of uranium, potassium and thorium elements, respectively. Although standard deviation values in these graphs remained in small intervals, this value remained relatively higher for Th. While uranium value gets the highest value in volcanites (Figure 11c), plutonites get the highest values in graphs of potassium (figure 11d) and thorium (figure 11e). The highest value representing of uranium in volcanites as shown in Figure 11c should be specialized to the study area. However, volcanic rocks may present extremely different values with respect to uranium content. While basic volcanic rocks are very low in U content, it is relatively higher in acidic volcanic rocks. Volcanic rocks within the area in this study were simplified and presented without considering their origin (Figure 3). While volcanic rocks extending in the northern parts of the region are basic, the Kötüdağ volcanite extending in the southern parts are mainly acidic volcanic products (Section 2.2.4). U anomaly in figure 11c might be showing that samples were collected more preferably from acidic volcanites.

RESULTS

This study was performed in area which covers the largest part of the Kırşehir Massif in the Central Anatolia (Figures 1 and 2). The shallowest area of the Curie point depth which is 580°C takes place around Kırşehir with 11 km's, the deepest part occurs around Nevşehir with 15 km's (Figure 6). Effective anomaly directions on Curie point depth map is approximately in E - W. When this and the geological maps were compared (Figure 3), it was seen that the shallowest anomaly was on the Kırşehir - Yozgat line. It was also observed that rocks spreading on this area consist of granitoids in west and east and of metamorphic rocks around Kırşehir. Both rock groups possess sufficient thermal conductivity to permit heat flow to approach the surface. Besides, regional tectonomagmatic events also have a significant role for the Curie depth to be shallow in addition to the thermal conductivity. These two maps are generally compatible with each other (Figure 3 and Figure 6).

Heat flow (Figure 7) and radiogenic heat production maps (Figure 8) of the study area were produced by using data of previously performed aeromagnetic, on land regional scaled gravity and aerial gamma ray spectrometry studies in the region. The heat flow of the region showed an anomaly which is dominant in north - south directions (Figure 7). On the heat flow map, there was observed a variation between 50 mW/m² and 110 mW/m² and the average value was estimated as 72 mW/m². The anomaly of the region which its heat flow is high overlaps on granitoids spreading approximately in NW - SE directions along Aksaray - Ş. Koçhisar - Kaman - Keskin line on the geological map shown in figure 3. However; anomaly regions that have low heat flow correspond with areas where there are sedimentary and volcanic rocks on the geological map. In spite of the fact that there is morphologically considered a close relationship between the heat flow map and the Curie point depth map, a positive correlation could not be attained in this study. It was seen that effective anomaly directions on the Curie point depth map and the effective anomaly direction on the heat flow map had developed perpendicular to each other. On the other hand, looking at the tectonic position of the region (Figure 2), it can be seen that common directions of main structural elements are compatible to some extent with effective anomaly directions on the Curie point depth map. This

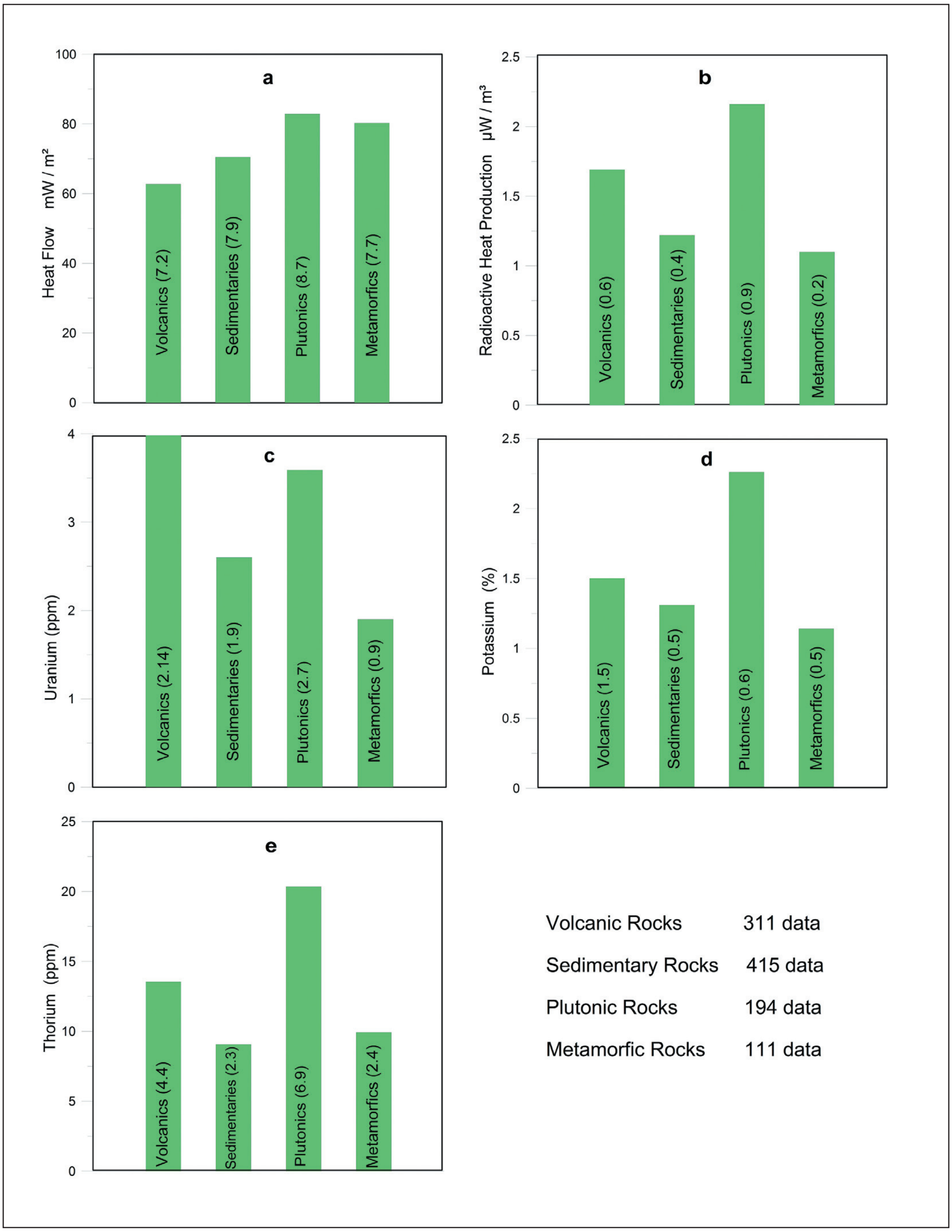

Figure 11- Average and standard deviation values of rocks within the study area a) heat flow, b) radiogenic heat production, c) Uranium, d) Potassium and e) Thorium.

compatibility suggests that, deep fault systems control the Curie depth at the same time as well.

In this study, the percentage ratios of the heat derived from two different heat sources (from mantle and the layer where the radiogenic heat production had occurred) were calculated and the map showing the distribution of percentage ratio of the mantle source heat was produced (Figure 10). According to this map, the heat originating from mantle in the study area shows variation in between 60% and 92%. When the mantle + radiogenic heats are accepted as 100%, the complementary ratios of the heat distribution originating from mantle will give us the distribution of the radiogenic heat. In this case, regions in which the radiogenic heat is the highest will correspond to the regions where the mantle source heat is the lowest. In accordance with this approach, when figure 10 is studied again, it will be seen that, regions where the radiogenic heat is the highest, are around Nevşehir, NE of Kaman and the zone enlarging over NW of Yozgat which is arranged along a thin line starting from the center of Kayseri. Geologically; Neogene aged volcanic and volcano sedimentary deposits with terrigenous clastics and carbonate deposits are successively observed as widespread in these regions. The radiogenic heat production in these parts rises up to 5.68 μWm^{-3} (Figure 8). These high radiogenic heat production zones generally overlaps granitoid areas on the western side of the study area and this is meaningful to a certain extent. Although volcanic and volcano sedimentary series are extensively seen around Nevsehir, occurring the highest radiogenic heat production values here indicates that concentrations of radioactive element in these rocks are rather high. Thus, when Figure 11b is studied, it could be seen that the heat production values of volcanic are not as much as plutonic rocks. Similarly; the heat production in terrigenous clastics and carbonates reaching high values suggest that there are high radioactive element concentrations in the source areas of these clastics and conclude sporadic enrichments in some basins (Figure 3).

Plutonic rocks in the study area (as average values) possess 2.16 μWm^{-3} radiogenic heat production; 82 mWm^{-2} heat flow; %2.26 potassium / 20.36 ppm Thorium / 3.29 ppm Uranium as being relatively higher compared to the average values of other rocks (Figure 11). Volcanites in radiogenic heat production follow up plutonites with 1.68 μWm^{-3}. Radiogenic heat productions of both sedimentary and metamorphics rocks are very close to each other and are successively around 1.25 μWm^{-3} and 1.20 μWm^{-3}. These values actually indicate that the radiogenic heat production heavily generated in magmatic and volcanic rocks and these values were not reached in other derived rocks although there had been enrichment processes. Hence; this case is clearly observed when looking at the concentration distribution of radioactive element. Although the uranium has a different behavior, almost all radioactive elements reach their peak values in plutonic rocks (however uranium gives a peak value in volcanic rocks). This case is followed by volcanic rocks. Both sedimentary and metamorphic rocks too take their places in succession having approximate half values.

Human health and environmental conditions should also be carefully treated since radiogenic heat production is rather high in magmatic and volcanic rocks in the region. Within this scope, this scientific finding would be useful both to differentiate mantle and radiogenic heats in geothermal energy surveys, to define reservoirs in the region and to reduce probable radioactive effects to human settlements and food chain to a minimum.

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