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CONTENTS

Facies Characteristics And Control Mechanisms of Quaternary Deposits In The Lake Tuz Basin
........Alper GÜRBÜZ and Nizamettin KAZANCI 1

Neotectonic-Period Characteristics, Seismicity, Geometry And Segmentation of The Tuz Gölü Fault Zone
........Akın KÜRÇER and Y. Ergun GÖKTEN 19

Neogene Stratigraphy And Paleogeographic Evolution of The Karaburun Area, İzmir, Western Turkey
........Fikret GÖKTAŞ 69

Benthic Foraminiferal Fauna of Malatya Oligo-Miocene Basin (Eastern Taurids, Eastern Turkey)
........Fatma GEDİK 93

Protolith Nature And Tectonomagmatic Features of Amphibolites From The Qushchi Area, West Azerbaijan, NW Iran
........Mohssen MOAZZEN 139

Glauberite-Halite Association In Bozkır Formation (Pliocene Çankırı-Çorum Basin, Central Anatolia, Turkey)
........İlhan SÖNMEZ 153

Estimation of Swelling Pressure Using Simple Soil Indices
........Kamil KAYABALI and Özgür YALDIZ 177

Two Examples For Imaging Buried Geological Boundaries: Sinkhole Structure And Seyit Hacı Fault, Karapınar, Konya
........Ertan TOKER, Yahya ÇİFTÇİ, Aytekin AYVA and Akın KÜRÇER 189

The Assessment of Geothermal Potential of Turkey By Means Of Heat Flow Estimation
........Uğur AKIN, Emin Uğur ULUGERGERLİ and Semih KUTLU 201

A Brief Note On Mineral Evolution And Biochemistry
........José Mario AMİGO 211

Critisism on the paper “Possible Incision of The Large Valleys In Southern Marmara Region, Turkey
(Nizamettin KAZANCI, Ömer EMRE, Korhan ERTURAÇ, Suzanne A.G. LEROY, Salim ÖNCEL,
Özden İLERİ and Özlem TOPRAK)
........Nizamettin KAZANCI 219

Acknowledgement 221

Notes to the authors 223

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THE ASSESSMENT OF GEOTHERMAL POTENTIAL OF TURKEY BY MEANS OF HEAT FLOW ESTIMATION

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Heat flow, Curie temperature, Curie point depth, geothermal gradient

ABSTRACT

In this study, the heat flow distribution of Turkey was investigated in the interest of exploring new geothermal fields in addition to known ones. For this purposes, the geothermal gradient was estimated from the Curie point depth map obtained from airborne magnetic data by means of power spectrum method. By multiplying geothermal gradient with thermal conductivity values, the heat flow map of Turkey was obtained. The average value in the heat flow map of Turkey was determined as 74 mW/m^2. It points out existence of resources of geothermal energy larger than the average of the world resources. in terms of geothermal potential, the most significant region of Turkey is the Aydin and its surrounding with a value exceeding 200 mW/m^2. On the contrary, the value decreases below 30 mW/m^2 in the region bordered by Aksaray, Niğde, Karaman and Konya. The necessity of conducting a detailed additional studies for East Black sea, East and Southeast Anatolia is also revealed.

1. Introduction

Much of the heat on earth crust originates from the mantle and a very small amount from the decay of radioactive elements (radiogenic source heat). The heat from radiogenic origin is produced by short and long half-life isotopes on earth crust. While radiogenic isotopes with short half-life were effective during the first periods of the earth, the isotopes with long half-life (^{235}U, ^{238}U, ^{232}Th and ^{40}K), however have taken place in the production of radiogenic heat starting from the first period of the earth till today (Göktürkler, 2002). The relative ratios of sources of the heat energy at any point on the earth can be estimated as percentage (Akın and Çiftçi, 2011).

In Turkey, the most of the places with the high heat flow where both volcanic and/or tectonic activity occurred and geothermal sources exist (Figure 1).

Heat flow can be obtained via direct or indirect methods. Some of the direct methods are as follows.

The silica geothermometer calculates the heat flow using SiO_2 amount dissolved in spring waters (Fournier and Rowe, 1966, 1977). The calculation of heat flow by Bullard method is a preferred method for the wells drilled especially in sedimentary rocks (Bullard, 1939). The method is also useful when irregular heat gradient and conductivity are observed.

The modeling studies can take the different types of groundwater regime into calculation of subsurface heat distribution. In addition to these methods, the heat flow can also be calculated with the thermal gradient method. The thermal gradient is the rate of change of heat with respect to depth. The temperature change in vertical direction (dT/dz) is considered for the heat flow calculation. The unit of the coefficient

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of thermal conductivity in SI system (International System of Units) is defined as W/m°C. If the heat in any medium, flows normal to surfaces within unit sections which are parallel to each other and reaches the steady state then the heat flow is equal to the multiplication of thermal conductivity by the thermal gradient.

There are studies which were carried out in the past using mentioned method and cover relatively narrow regions. The common point of previous studies is to discard the usage of the calculated rock thermal conductivities. Therefore; the researchers estimated the heat flow by using only one constant value for λ (the rock thermal conductivity coefficient) found in literature and considered to represent entire region.

Factors affecting the change in (λ) thermal conductivity coefficient during the formation of rock are as follows; temperature, pressure, porosity, density, grain size, degree of cementation, mineral and fluid content. In addition, porosity and ratio of water saturation are important. Depending on the water saturated or dry sample The differences can occur upto 30% for λ values estimated in the laboratory (Scharli and Raybach, 1984).

From 1969 to present, the heat flow studies, that uses different techniques and methods, have been subject to various geological and geophysical researches in many countries (İspir, 1972). Generally, heat flow values are higher than 83.8 mW/m^2 in tectonic zones and ocean ridges (Lee and Uyeda, 1965; Langseth and Taylor, 1967; McKenzie, 1967; Gorshkov, 1972; Zoneshin, 1975).

The heat flow is high in island arc formations, subduction zones, in deep fault zones and in the close vicinities of plate collision zones (Sclater, 1972). Over the mid ocean ridge, as moving away from the axis, a decline in the heat flow values is observed. This value becomes significantly low in oceanic trenches. Two out of three volcanoes are located in the Pacific Zone. The heat flow contribution varies depending on the geological age of tectonic unit; while Precambrian aged (>600 million years) geological formations possess low heat flow, Cenozoic aged (<70 million years) young folds possess a high heat flow.

Generally; the heat flows are usually high in volcanic regions but there are differences in heat flow values between old and young volcanic units, too. The heat flow has been a research topic in continental scale. EGT (European Geotraverse) project investigated the temperature variation along Europe. The temperature distribution along a line starting from the north of Scandinavia extending to the south of Crimea has been mapped upto depths of 60-70 km (Shen et al., 1991). The area has been divided into two regions in terms of its heat flow values, while the eastern part was represented with normal values (41.9 - 50.2 mW/m^2), the western part exceed to higher

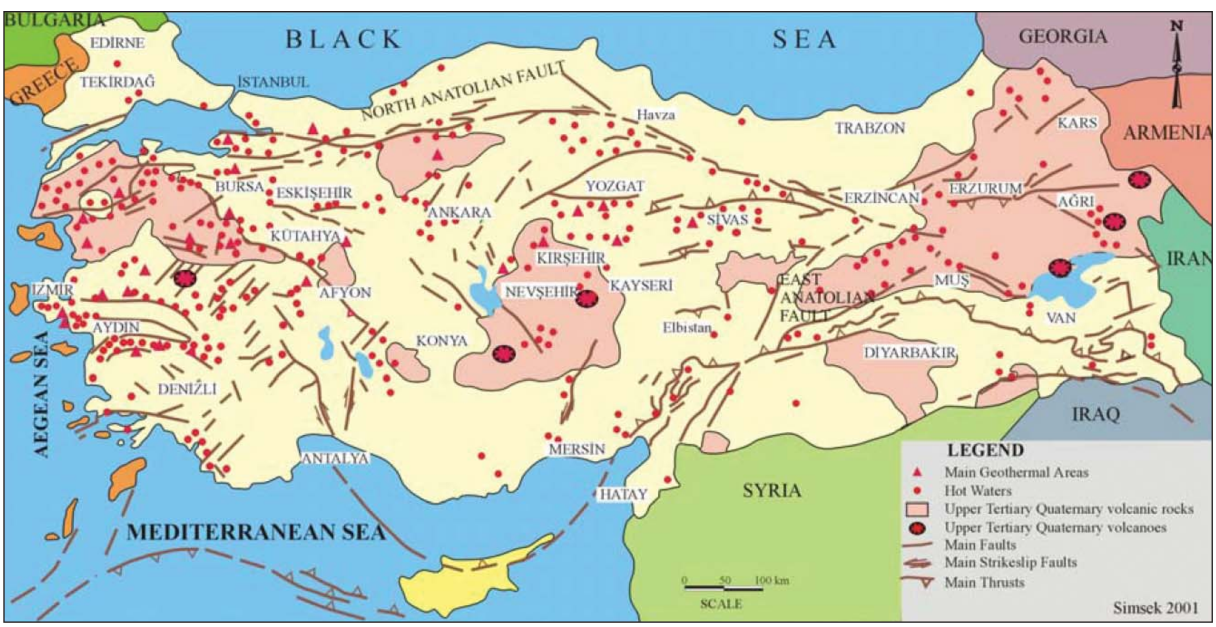

Figure 1- Map of geothermal resources and volcanic areas (MTA, 2014).

values (83.8 mW/m^2). Areas with low heat flow are where Precambrian shields are present. Although the heat flow values observed in Baltic, Ukrainian and Indian Shields are 36 mW/m^2, 29.33 mW/m^2 and 38.5 mW/m^2, respectively, heat flow values becomes significantly low in Precambrian platforms of Eastern Europe and Siberia (Tables 1 and 2).

High heat flow values have been encountered in grabens. Heat flow values for Ren Graben as 83.8-167.6 mW/m^2, Baikal Graben as 83.8-209.5 mW/m^2, Cambay Graben as 83.8-104.7 mW/m^2 have been measured (Gupta et al., 1970; Gorshkov 1972; Tissot and Espitalie, 1975).

Fytikas (1980), with his study in the Aegean Sea, determined three high heat flow regions extending along tectonic structures. The first region possesses a high heat flow which occasionally exceeds 120 mW/m^2 and extends along Palegonian - Parnos zone (interior side of the Hellenic island arc) passes through Astipalia and Kavaros islands reaches Bodrum – Karaada. The second heat flow region is in the Central Aegean, takes place at western end of İzmir – Ankara zone and values exceed 100 mW/m^2. The last region forms a belt of high heat flow anomaly covering the shores of Macedonia, the northern Aegean islands, Biga and Gelibolu peninsulas.

Country-wide or local scale heat flow estimations of Turkey have been studied by many researchers. In these studies, it is found that high heat flow values for west Mediterranean while low values for east Mediterranean have been obtained. Besides, low heat flow values for Black Sea have been observed. In reality, due to rapid sedimentation, if a correction factor is applied, Black Sea appears to be a high heat flow zone (Ericson, 1970).

Tezcan and Turgay (1991) obtained the heat flow map and temperature distribution map at the depth of 1000 meters, selecting the average thermal conductivity coefficient as λ=2.1 W/m^{o}K^{-1} for Turkey. İlkışık (1995) conducted regional heat flow studies in western Anatolia using silica geothermometer on hot springs. Besides, he also estimated the average heat flow as 107±45 mW/m^2 and stated that it was 50-60% higher than the world average. Pfister (1995) did the detailed heat flow investigation in Marmara region. The heat flow distribution of the Aegean region was assessed with geothermal gradient measured in wells (Yemen, 1999).

Heat flow can be estimated from magnetic data indirectly (Akın and Duru, 2006; Akın et al. 2006). The aeromagnetic anomaly map of Turkey (Figure 2) defines the major tectonic and geological units of Anatolia, and reveals anomalies of many subsurface structures which cannot be observed on surface geology. Besides, it is also used to estimate the depth of magnetic basements and location of basins in present geography, even if they were formed at different geological times, it carries much information for the exploration of mineral deposits, geothermal resources, oil and gas bearing unit, etc.

Bhattacharyya (1965, 1966), Spector and Bhattacharyya (1966) used the power spectrum method, a statistical approach, in interpreting the potential field data. It is used to determine the depths of underground structures which cause a magnetic anomaly (Spector ve Grant, 1970). This method can

Table 1- Heat flow measurement values in various geological structures of continental crust (after Lee and Uyeda, 1965).

Geological Structure	**Average Heat Flow (mW/m^2)**
Precambrian Shields	38.5 ± 29.3
Paleozoic aged Orogenic areas	51.5 ± 16.76
Mesozoic-Cenozoic aged Orogenic areas	80.4 ± 20.5
Cenozoic aged volcanic areas (except for geothermal field)	90.5 ± 19.2

Table 2- Heat flow measurement values in various structures of oceanic crust (after Lee and Uyeda, 1965).

Heat flow in Oceans	**Average Heat Flow (mW/m^2)**
Oceanic Basins	53.6 ± 22.2
Mid-Ocean Ridges	76.2 ± 65.3
Oceanic depressions (trenches)	41.8 ± 25.5

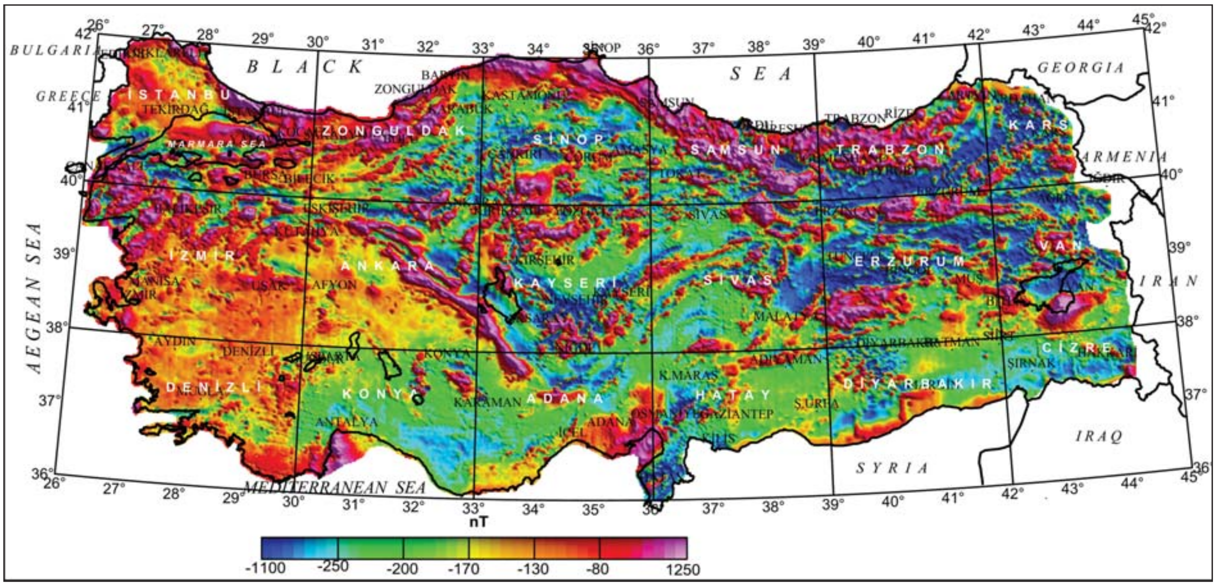

Figure 2- Aeromagnetic anomaly map of Turkey.

be applied both on profile and on map data (Figure 3). When the method is applied on gravity data, it estimates the lower depth of the main body on the other hand; when applied on magnetic data, it delineates the depth at which the Curie temperature is reached. Curie point temperature (CPT) is the critical temperature which is necessary for a ferromagnetic substance to lose its stable magnetism. Each substance has different Curie critical temperature. This temperature is named as the "Curie temperature" in the memory of Pierre Curie who studied in the area of paramagnetism.

The map of Curie point depth (CPD) of Turkey was produced by Karat and Aydın (2004) by means of the power spectrum. They showed that hot spring outflows are more dense in areas where the CPD is estimated shallow especially in Western and Central Anatolia regions (Figures 1 and 4).

It is know that hot spring outflows occurs along tectonic lines along the northern boundary of the shallower CPD zone covering western Anatolia and vicinity of Ankara, and earthquake epicenters are condensed especially on margins of shallow areas in West Anatolia. Additionally, shallow CPD at known oil fields in Southeast Anatolia presents structural

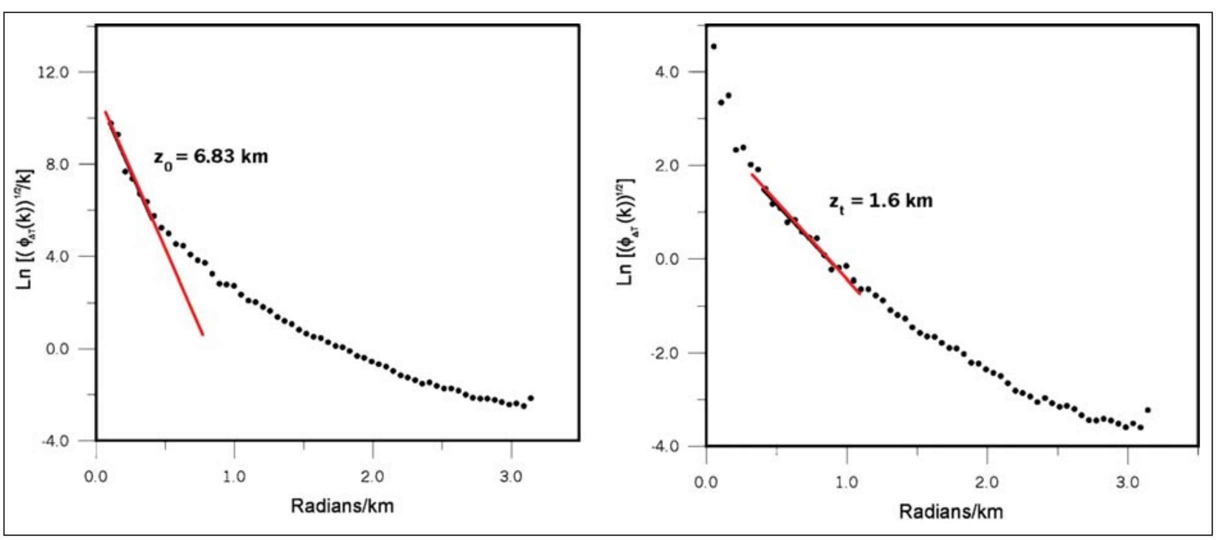

Figure 3- Sample curve for the Curie point depth of one block (north of Lake Van) (modified from Aydın et al., 2005).

similarities with Thrace region (Karat and Aydın, 2004) (Figure 4).

Şalk et al. (2005) estimated Curie point depths of the western Anatolia applying the power spectrum method to Magsat magnetic data with using the thermal conductivity value of 2 W/m°C. They showed that Curie point depths of young volcanic rocks and metamorphic units of the western Anatolia and heat flow values were coherent. They also revealed the relations between the source of heat in geothermal fields and deep magmatic bodies, young volcanic rocks which have not yet lost their heat and structural fault systems.

In this study, Curie point depths of Turkey are calculated by using aeromagnetic data of Turkey. Being a difference from previous research, instead of using fix thermal conductivity value, various in-situ conductivities, gathered in various projects, are used to produce an updated heat flow map. Obtained results are compared with previous result to check consistency and presented here for consideration of researchers

2. Geothermal Potential of Turkey

Geothermal fields are areas where the heat is transferred. Areas in which the heat flow is between 0-125.7 mW/m^2 are called as normal fields, whereas the areas in which the heat flow is higher than 125.7 mW/m^2 is called as geothermal fields.

Turkey has a large geothermal potential. There are more than 170 economically important geothermal fields and 1500 hot and mineralized water sources in the country. Spring outflows and reservoir temperatures of these waters are in between 20°-242°C (Figure 1). Geothermal spots usually appear around major grabens in western Anatolia, along the North Anatolian Fault Zone (NAFZ) and in the volcanic regions in Central and East Anatolian (Şimşek et al., 2005). The geothermal heat potential of Turkey is considered to be 31500 MWt at present conditions. General Directorate of Mineral Research and Exploration (MTA) has explored the presence of 190 geothermal fields within 50 years period. Geothermal fields through Turkey show a distribution as 79% in west Anatolia, 8,5% in Central Anatolia, 7,5% in Marmara Region and 0,5% in other areas. 94%, of the geothermal sources are in low to medium temperature and used for heating, thermal tourism and in mineral production. The remaining 6% however, is suitable for the production of electrical energy (MTA, 2014).

3. Geophysical Data and Technique

Aiming to provide a base information to explore the underground resources of Turkey, within the Department of Geophysical Researches of the MTA, aeromagnetic studies started in 1978 and completed in 1989. Total of 460.000 km aviation research was carried out over sea, lake and on land, covering an area of 813.639 km^2. However, due to border agreements between Turkey and its neighbor countries, these researches had to be stopped at 5 km

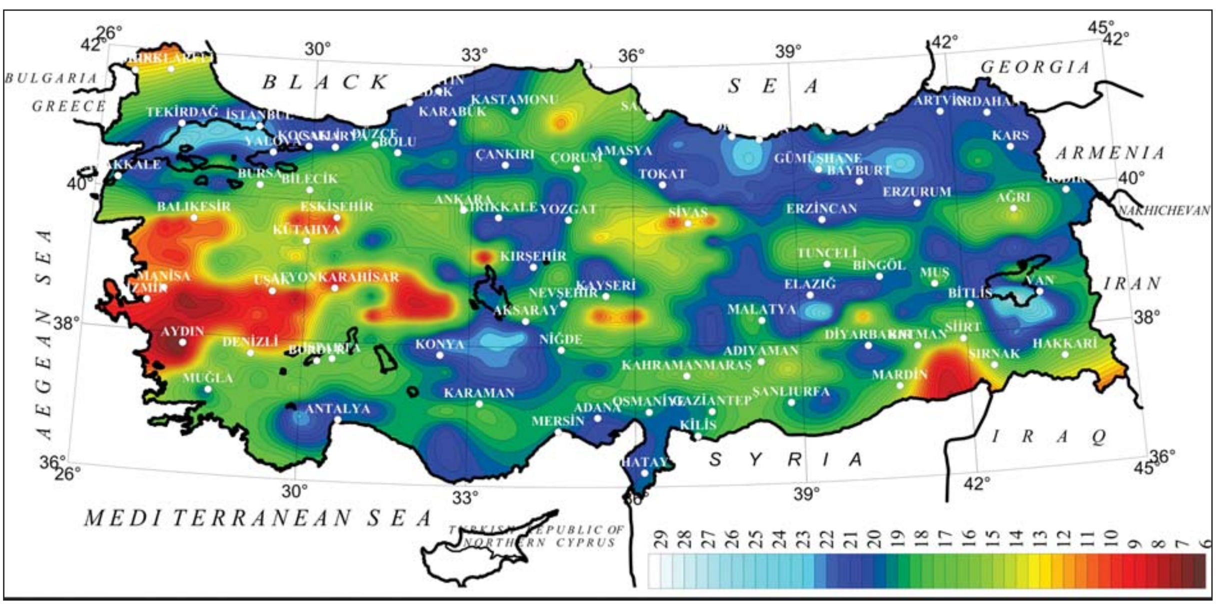

Figure 4- The map of Curie point depth (modified from Aydın et al., 2005).

to Syrian, Iranian and Iraqi borders and at 15 km to Former Soviet Union, Greek and Bulgarian borders. Flight lines were at a height of approximately 2000 feet (600m) and their directions were selected according to topographic obstacles and, mostly, the geological factors. Flight line intervals were kept around 1 to 5 km depending on existence of possible geothermal, mineral explorations and other potential resources. Measurements of diurnal change were recorded by magnetic base station in each flight sector and necessary corrections were completed by defining heading error. Different Data sets recorded on same sectors but at different times (considering annual changes of the geomagnetic field) were controlled and tied eachother by using the common lines which have same flight elevations (Karat and Aydın, 2004). IGRF 1985 (International Geomagnetic Reference Field) were applied to Aeromagnetic data for reduction.

Aydın et al. (2005) gridded the aeromagnetic data in size of 1x1 km and applied the spectral analysis technique over 380 blocks.

Using the technique suggested by Spector and grant (1970) and improved by Tanaka et al. (1999) and Okuba et al. (1985) Depth of Curie isotherm map was produced. The depth of source of magnetic anomaly was given in Equation 1 (Figure 3).

$$Z_b = 2Z_o - Z_t \qquad 1$$

where;

Z_b, lower depth of the magnetic source,

Z_o, depth of the center of the magnetic source,

Z_t, upper depth of the magnetic source.

Karat and Aydın (2004, 2005), with their estimation of Curie depth points, revealed that the western Anatolia was shallower than other regions. In the area covering Aydın-Denizli-Uşak and extends in west east directions, the depth was between 6 to 10 km. it is seen that Curie depth point is the shallowest in Aydın and its vicinity located in Menderes graben (Figure 4). In orogenic belts and high plateaus the calculated depths were between 20 to 29 km. The geothermal gradient was calculated from each grid cell of the map of Curie point depth and used for the map of heat flow.

As stated before, If the heat in any medium, flows normal to surfaces within unit sections which are parallel to each other and reaches the steady state then the heat flow, as given in Equation 2, is equal to the multiplication of thermal conductivity by the thermal gradient.

$$q=\lambda*(dT/dz) \qquad 2$$

where

q heat flow,

λ thermal conductivity coefficient of rock,

dT/dz geothermal gradient.

In this study, we used 579 the rock thermal conductivity values (λ), recorded through Turkey, by Karlı et al. (2006). In Table 3, λ values for Manisa–Çataloluk is given. In Equation 2, using in-situ thermal conductivity values instead of fixed λ coefficient, a new heat flow map was obtained (Figure 5).

Rock thermal conductivity data are not sufficient in eastern Black Sea, southeastern and eastern Anatolia regions. In future, when the number of samples is increased, much detailed maps in those regions will be possible to generate.

In western Anatolia horst graben systems of Menderes massif caused a crustal thinning. Due to this thinning, Curie point depths are shallow (between 7.3 – 15 km) in Aydın, Denizli and Uşak (Karat and Aydın 2004; Aydın et al., 2005). İzmir and its vicinity, with the average heat flow value of 101

Table 3- Measurement values of rock thermal conductivity coefficients taken by QTM (Quick Thermal Measurement) device (after Yemen, 1999).

Location	**Rock lithology and thickness (m)**		**QTM measurement λ (W/m°C)**
Manisa–Çataloluk	Marl	0-53	1.797
Manisa–Çataloluk	Pebble-tuff	53-85	1.375
Manisa–Çataloluk	Sandstone	85-122	3.228

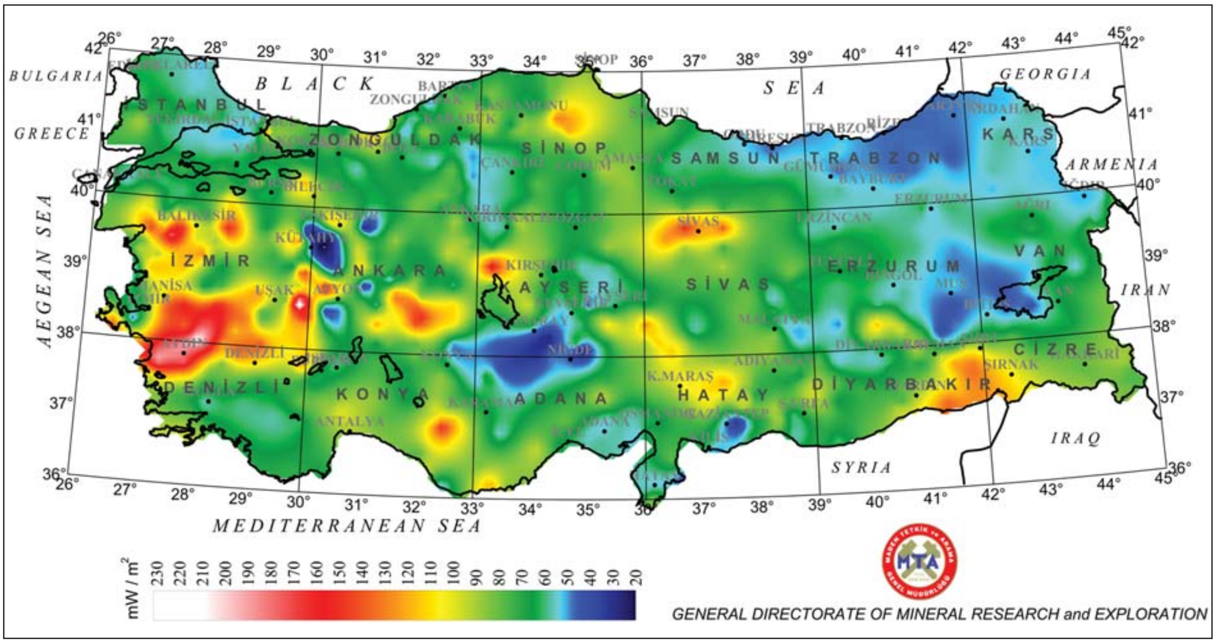

Figure 5- Updated heat flow map of Turkey.

mW/m^2, forms the most important region of Turkey in terms of geothermal potential.

At the north of Ankara-Erzincan Suture zone, in the Eastern Black Sea Region Heat flow values in Ordu, Artvin and Bayburt regions, are estimated as 57 mW/m^2 , 47 mW/m^2, 55 mW/m^2, respectively.

Heat flow values decrease, where the crust thickens, in areas of Bingöl, Bitlis, Muş, Batman and Van which are located as parallel to north of Bitlis Suture Zone. It was determined that lithological characteristics played an important role on the change of heat flow. Relative increases in the heat flow have become distinct in areas where granitoid, volcanite and gneisses are dense in the region.

Two areas are observed in the north and east of Lake Van, considered to be associated with each other with Curie point depths of 17-18 km, (Karat and Aydın, 2004).

Deep well drillings carried out by TPAO in Nemrut Mountain revealed that the temperature was less than expected. The heat flow map shows low heat flow values as 55 mW/m^2 in northeast of Lake Van (in the vicinity of Muradiye) and 46 mW/m^2 in Nemrut Mountain. The heat flow value is 71 mW/m^2 over the young volcanic rocks located in the anomaly region spreading at south of Ağrı and its surround.

In tectonically active areas of Anatolia and the regions of the young volcanism, the high heat flow indicates the enrichment of geothermal resources. The Curie point depth of the region between Sinop, Samsun and Çorum areas, which is the shallowest section of the Black Sea, is 11.6 km (Karat and Aydın, 2004). Hot springs located on margins of the anomaly support a crustal thinning in this place.

In the heat flow map, maximum values; 93 mW/m^2 at the southeast of Kastamonu and 128 mW/m^2 at the region between Sinop, Samsun and Çorum appear to be compatible with each other.

The Curie point depth of the most active faults in the shear zone between Erzincan–Tunceli in Turkey is 16 km. There are significant numbers of hot springs in the region. The values of 56 mW/m^2 were detected in Bingöl. This incompatibility, as mentioned in discussion, occurs due to lack of sufficient data cluster in eastern Anatolia region.

Along the narrow belt which starts from Hakkari to north of Urfa then to the north Adana and continue extending westward, shallow Curie point depths are observed. Curie point depth is getting shallow up to 11 km (Karat and Aydın, 2004). Estimated heat flow values in region between Şırnak, Siirt, Batman, Mardin region, in the north of Diyarbakır and Karacadağ are 132 mW/m^2, 116 mW/m^2 and 55 mW/m^2, respectively.

Although Erciyes is located in the area (Figure 1),There is not any distinctive hot springs in the south of Kayseri. In the heat flow map, along a narrow band extending from Kayseri to Gaziantep there is high heat flow maximum value of which increases up to 116 mW/m^2.

Trabzon and Kars and their vicinity are the lowest areas in terms of heat flow values and they are 52 mW/m^2 and 54 mW/m^2, respectively.

The maximum, minimum and average heat flow values together with Curie point depths for Turkey given in Table 4.

4. Discussion and Suggestions

The rock thermal conductivity of 579 samples collected throughout Turkey was assessed and the heat flow map of Turkey was produced. The number of rock thermal conductivity is not sufficient nor does it exhibit a homogenous distribution. These data display a sparse distribution in Eastern Black Sea, Southeastern and Eastern Anatolia regions. Through the additional researches, any increment in the number of samples will also enhance the value of maps that will be reproduced in future.

In the heat flow map of Turkey, the average heat flow value of the country was determined as 74 mW/m^2.

The resultant map of this study revealed that Turkey possesses a great geothermal potential. in terms of geothermal resources, the most significant region of Turkey is İzmir sheet in 1/500.000 scale with the average value of 101 mW/m^2. The Curie point depth within this region varies in between 6 to15 km.

The shallowest areas in the region are in Aydın and Denizli which are located in Menderes Graben (Karat and Aydın, 2004; Aydın et al., 2005). The minimum and maximum values in this region are also the highest and lowest values of Turkey as; below 30 mW/m^2 between Kütahya and Eskişehir, whereas as 229 mW/m^2 between Uşak and Afyon.

The average depth in Trabzon, Samsun and İstanbul sheets is 20 km. Their related average heat flow values were also detected as relatively low. Trabzon sheet especially in terms of heat flow were found to be the weakest region of Turkey in with the value of 52 mW/m^2 (Figure 1 and Table 4).

Table 4- The average heat flow and Curie values for Turkey on 1/500 000 scaled map.

1:500.000 scaled sheet	**Maximum (mW/m^2)**	**Minimum (mW/m^2)**	**Average (mW/m^2)**	**Average Curie Depth (km)**
İstanbul	123	51	66	20.3
Zonguldak	113	48	70	18.7
Sinop	129	52	78	17.9
Samsun	100	59	74	20.4
Trabzon	63	45	52	21.5
Kars	80	50	54	19.5
İzmir	229	29	101	12.2
Ankara	166	20	81	15.4
Kayseri	164	26	72	18.6
Sivas	152	50	81	17.5
Erzurum	116	41	61	19
Van	87	42	62	19.6
Denizli	191	56	86	16
Konya	148	48	80	18.9
Adana	118	34	67	19.6
Hatay	120	33	78	17.7
Diyarbakır	135	54	83	17.1
Cizre	126	64	87	19.3

In the light of the insufficient data Ankara, does not seem to be prosperous in terms of hot water sources and geothermal fields. Therefore; additional studies to be carried out on the Ankara sheet will probably define better the geothermal potential of the region.

Although Diyarbakır and Cizre have considerably high heat flow, the absence of hot water sources and geothermal fields are highly remarkable (Figure 1). Cizre has an approximate Curie point depth of 19.3 km and a low geothermal gradient with respect to Diyarbakır.

The Curie point depths of Adana, Van, Erzurum, Kars and Konya vary in between 18.9 to 19.6 km, nevertheless exhibit relatively weak characteristic in terms of heat flow.

Curie point depths on Sivas, Hatay and Sinop sheets show variation between 17.5 to 17.9 km. These values are shallower than the average Curie point depth of the country. Heat flow values of sheets are compatible with shallow Curie point depths and are above the country average. Sinop sheet which houses one part of the North Anatolian Fault system is as dense region in terms of hot water sources such as Zonguldak sheet and hot springs generally take place along the fault system.

Kayseri sheet which covers most of the Kırşehir massive remains below the country average with the Curie point depth of 18.6 km and heat flow value of 72 mW/m^2. Akın and Çiftçi (2011) presented that a some part of the heat flow of this sheet is originated from the radiogenic heat production. Volcanic rocks are dominant in the area. in terms of hot springs, geothermal fields and volcanic outcrops It is richer than many regions.

5. Results

Taking Curie point depth map of previous research as a base, using thermal conductivity values obtained in various projects a new heat flow map of Turkey was produced. The result obtained are in accord with the field observations. In addition to existing field, it is revealed that additional research needs to be conducted for the fields of east black sea, east Anatolia, south east Anatolia

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